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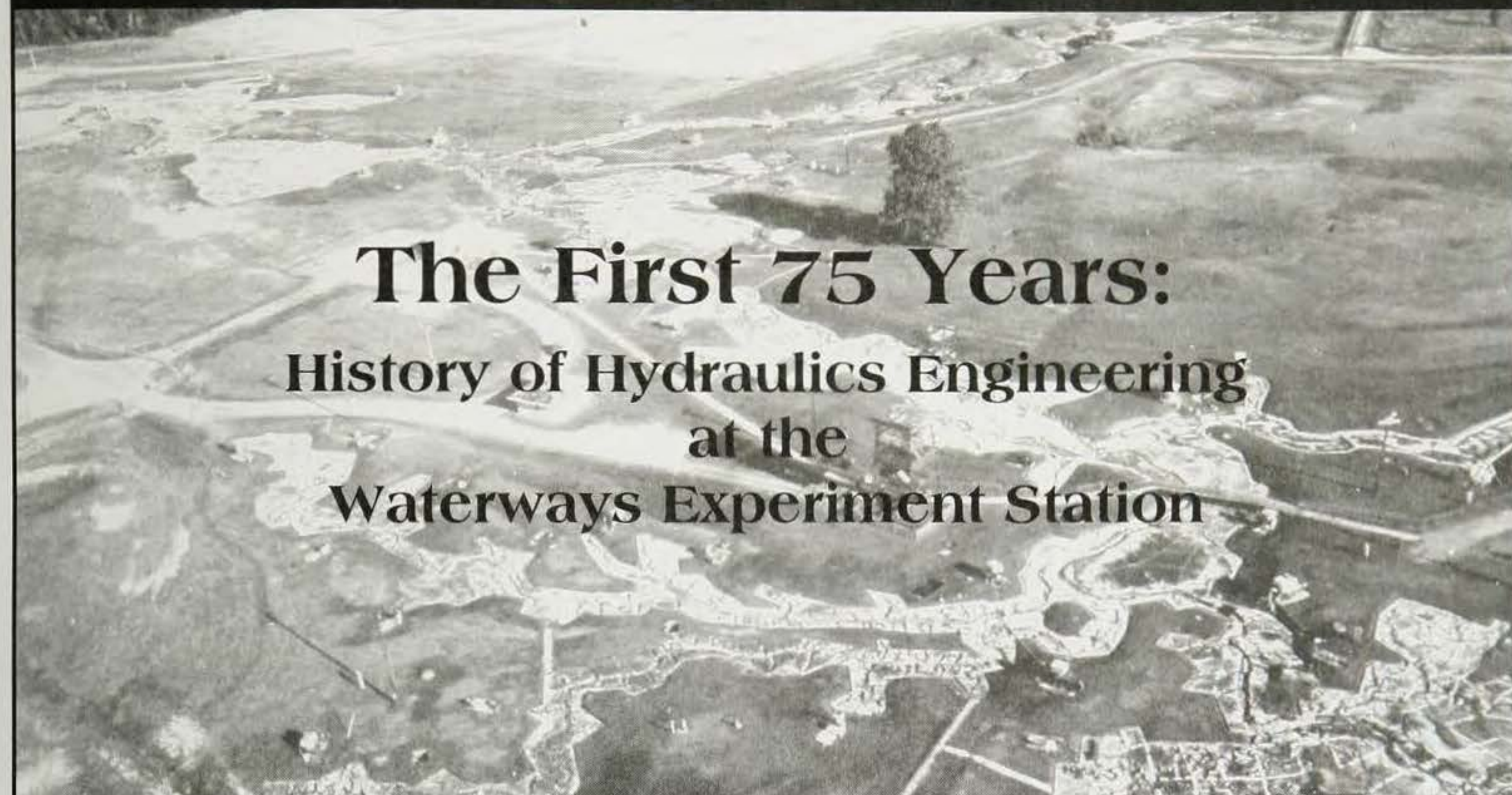

The First 75 Years:

History of Hydraulics Engineering at the Waterways Experiment Station

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On the Cover:

Aerial view of the Mississippi Basin Model looking toward the Gulf of Mexico. (Ohio River Basin in lower right foreground; Atchafalaya Basin in extreme upper left.)

Main Building in 1981.

The First 75 Years:
History of Hydraulics Engineering at the Waterways Experiment Station

by
Dr. Ben H. Fatherree

U.S. Army Engineer Research and Development Center
Vicksburg, Mississippi
2004

Preface

Dr. James R. Houston, Director, U.S. Army Engineer Research and Development Center

The history of engineering is the story of men and women in their attempts to understand, control, and accommodate their environment. In 1929 the U.S. Army Corps of Engineers established a small hydraulics laboratory in Vicksburg, Mississippi, in recognition of the increasingly vital role of scientific investigation in a laboratory setting as a necessary adjunct to the age-old practice of actual hands-on observation. Discoveries emanating from the laboratory, designated as the Waterways Experiment Station, paid immediate dividends and sparked a new confidence among the nation's engineering community to make bold advancements and challenge or affirm long-standing doctrines. This initial success broadened the Waterways Experiment Station's activities from mere hydraulic experiments for the Mississippi River to a Corp of Engineers-wide mission encompassing diverse fields of research.

In this way, that early hydraulics laboratory was the building block of the modern Corps of Engineers' research and development mission administered by the U.S. Army Corps of Engineers, Engineer Research and Development Center (ERDC). Headquartered at the Waterways Experiment Station reservation, the ERDC continues the tradition of advancing the limits of the engineering frontier. From its modest beginnings in hydraulics experimentation, the Corps of Engineers' research and development mission now spans the globe—from building better levees on the Mississippi River to supporting our military operations in Iraq, the ERDC is there; from providing solutions to benefit threatened and endangered species to providing the nation's warfighters with superior knowledge of the battlefield, the ERDC is there; from building sustainable military bases at home to nation building abroad, the ERDC is there.

The *History of Hydraulics Engineering at the Waterways Experiment Station* traces the evolution of hydraulic engineering at the Waterways Experiment Station from the establishment of a small, narrowly focused laboratory in 1929 through the impressive achievements in the dawn of the twenty-first century. It is, however, more than an unadorned compendium of technological advances and setbacks. Intertwining complex human factors, administrative and organizational developments, and technological progress, this history attempts to capture the total institutional experience of this outstanding national asset.

The Author

Ben H. Fatherree is a native of Quitman, Mississippi. Chair of the Social Sciences Department and Professor of History at Hinds Community College, Raymond, Mississippi, he holds a Ph.D. in history from Mississippi State University, was a Visiting Scholar at the Hoover Institution on War, Revolution, and Peace at Stanford University, and studied as a National Endowment for the Humanities Fellow at Columbia University. While serving as historian for the U.S. Army Engineer District, Vicksburg, on a part-time basis from 1987 to 1989, Fatherree published numerous historical articles.

Acknowledgments

As in the case of the history of geotechnical engineering at the Waterways Experiment Station (WES), this work was the product of many hands and minds. Early guidance was provided by the late Dr. Michael C. Robinson, former historian and Public Affairs Chief, U.S. Army Corps of Engineers, Mississippi Valley Division. Invaluable assistance was also provided by Dr. William H. McAnally, Chief of the Estuaries and Hydrosciences Division, WES Coastal and Hydraulics Laboratory, who served as project coordinator. Richard A. Sager, former Acting Director, WES Hydraulics Laboratory, and Dr. James R. Houston, Director, U.S. Army Engineer Research and Development Center, and former Director, WES Coastal and Hydraulics Laboratory, were also more than generous with their support and input.

Particular thanks must go to the personnel of the Coastal and Hydraulics Laboratory, both past and present, who gave so willingly of their time and expertise and who are too legion to name individually. However, the late Frederick R. Brown, WES Technical Director from 1969 to 1985, freely shared his WES memories. In addition to McAnally, Dr. Billy H. Johnson, John F. George, and Thomas J. Pokrefke were especially helpful in providing technical interpretations.

Billy C. Bridges, Chief, WES Public Affairs Office, and Wayne A. Stroupe, WES Public Affairs Specialist, were invaluable in contributing insights concerning the operation of "the Station" and how best to get things done in an expedient manner. Nor could there be a more professional or helpful cadre than the staff of the WES Research Library, especially Deborah J. Carpenter. Thanks also go to Marilyn Holt and the staff of the WES Visual Production Center for their splendid efforts in designing and laying out this study.

Dr. William Baldwin and Dr. Martin Reuss, both senior historians with the History Office, U.S. Army Corps of Engineers, and Charles Camillo, the historian for the Engineer Research and Development Center, the Mississippi Valley Division, and Mississippi River Commission, reviewed this manuscript and made invaluable suggestions for its improvement. Their unique scholarly insights served as guidelines throughout.

Introduction

The history of hydraulics engineering at the U.S. Army Engineer Waterways Experiment Station (WES) and its organizational successor, the U.S. Army Engineer Research and Development Center (ERDC), is an inspiring story. Seventy-five years ago, an Army Engineer lieutenant carved a modest facility out of a creek bank in the wilderness near Vicksburg, Mississippi. Born in controversy, within 20 years that facility was internationally known and led the world in some research areas. Seventy-five years later, it continues as a leader in many engineering fields and shows every evidence that it will remain so in the future.

It has been a challenge to chronicle the evolution of WES. With the exception of the World War II era, a regular army officer served as the Station's chief administrator in the Corps of Engineers' chain of command from 1930 through 1992. Yet, nearly all other employees were civilians, with civilians holding the vital post of WES Technical Director from 1940. WES, therefore, historically operated under a splendid mix of civilian and military leadership. In 1992, however, a restructuring of organizational roles placed the overall leadership of the laboratories under the WES Director—a civilian position, with the army officer serving as WES Commander and Deputy Director. In 1999, WES was absorbed into ERDC, which was headquartered at the WES site. The WES Director's position was converted into the ERDC Director's position, which was charged with overall responsibility for the new organization and was permanently filled in May 2000 by Dr. James R. Houston. A full civilian ERDC Deputy Director's position was established at ERDC's Alexandria, Virginia site, and was permanently filled in October 2001 by Dr. Walter F. Morrison, Jr. The WES Commander, Colonel Robin R. Cababa, was reassigned to be the first ERDC Commander with responsibility for the ERDC installations, oversight of administrative functions, and assisting the Director and Deputy Director in planning and executing the technical program.

It has been an equal challenge to trace the evolution of the Hydraulics Laboratory, which in 1996 merged with the former Coastal Engineering Research Center to become the Coastal and Hydraulics Laboratory (CHL). CHL persists as one of the seven laboratories comprising the ERDC.

This study makes liberal reference to WES. This is by no means a slight toward ERDC, rather it represents an attempt to remain true to the historical accuracy of the time period covered. Moreover, I am not (it will become apparent) an engineer. Herein, the goal is to provide the reader with the history in nontechnical terms of hydraulics engineering by the Corps of Engineers.

The history of engineering is the story of men and women in their attempts to understand and control the environment. The Hydraulics Laboratory is a story filled with successes, failures, surprises, and all other elements of human existence. It is the story of Lieutenant Herbert D. Vogel, a 29-year-old sent with orders to construct a laboratory "gradually as information develops" in Vicksburg (a place he knew only as "a long dusty ride with a cemetery at the end"). It is as well the story of Garbis H. Keulegan, an inspiring figure who began his WES career at the age of 72 and retired (again) at the age of 98. It is further the story of a remaining multitude of engineers, technicians, and support staff who made WES what it is.

This work is first dedicated to the people who chose the most common compound in nature – water – as the focus of their engineering careers. It is second a tribute to their discoveries and inventions, their feats and failures, that surround our lives.

Contents

1 In the Beginning

The Waterways Experiment Station

Located in Vicksburg, Mississippi, the Waterways Experiment Station reservation is the largest civil engineering and environmental quality research and development (R&D) complex in the Department of Defense. After nearly seven decades of independent status within the U.S. Army Corps of Engineers, "the Station," internationally known by the acronym "WES," now serves as the headquarters for the U.S. Army Engineer Research and Development Center (ERDC), a major subordinate command element within the Corps tasked with executing the agency's R&D mission. The Corps relies on ERDC laboratories at the WES reservation and at Champaign, Illinois, Hanover, New Hampshire, and Alexandria, Virginia, to perform studies in all phases of its mission. Part of that mission is to act as the primary national agency responsible for

The U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

flood control, river and harbor navigation, and numerous other activities involving hydraulic engineering. WES, in fact, was established originally in 1929 to assist the Corps in that area of its mission, and the Station has served as the Corps' hydraulic engineering facility for 75 years. The Station's workforce in 1997 numbered nearly1,500, including about 650 engineers and scientists, 198 with doctoral degrees.

In addition to serving the needs of the Corps, laboratories at the WES reservation have historically assisted Federal agencies, state and local governments, foreign governments, and occasionally private clients. Just prior to their consolidation into ERDC, WES laboratories annually engaged in more than 2,400 projects—large and small—for approximately 120 sponsors, with a budget exceeding $260 million. This highlights a unique aspect of the Corps' R&D mission—begun by WES at its inception—that sets the ERDC apart from most other military and governmental activities. The R&D mission does not rely on direct funding from the Army or a separate Federal appropriation for the majority of its operations. Instead, civilian and military clients reimburse ERDC for the bulk of its activities, a highly unusual, but effective, business model among government entities.

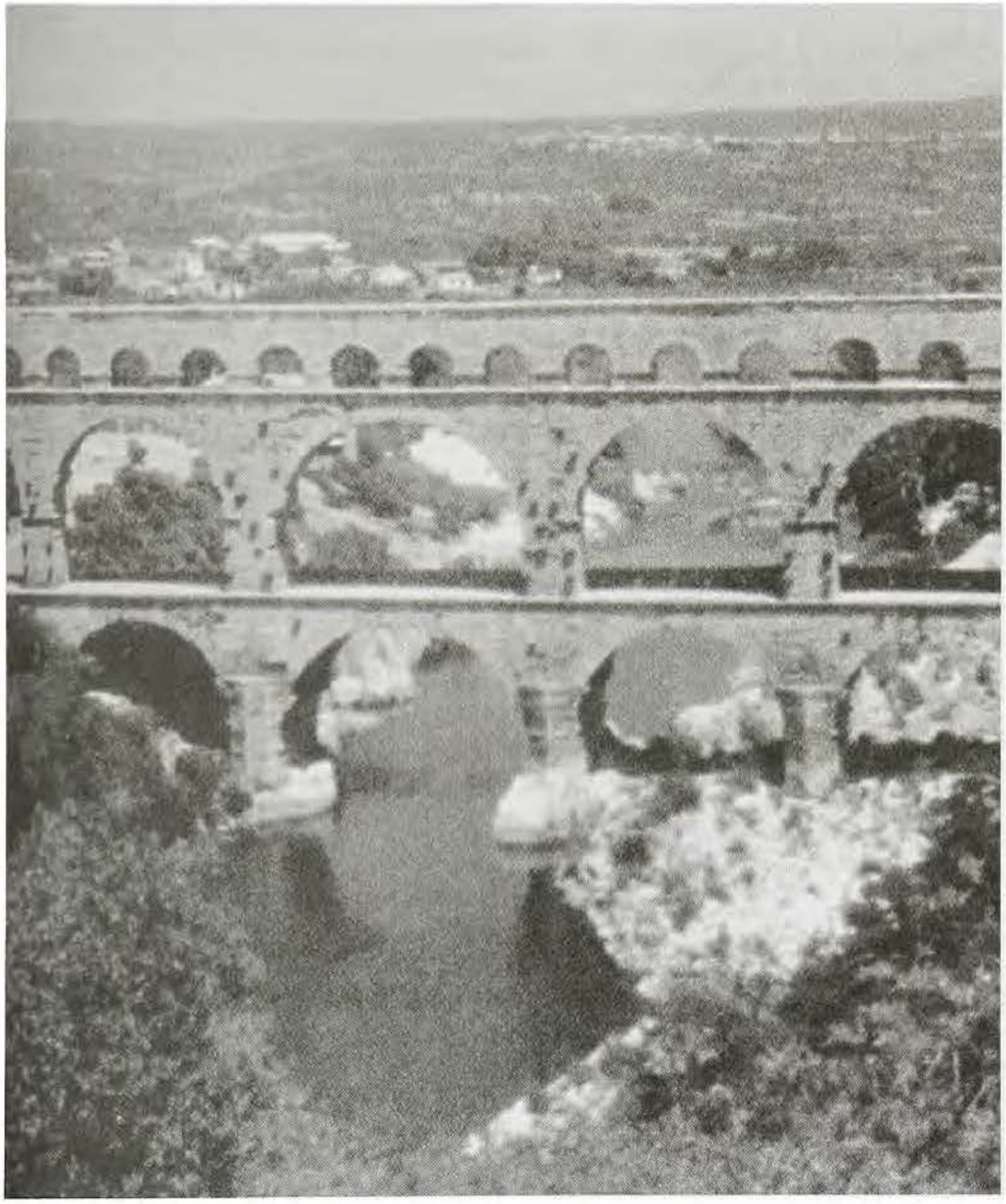
The R&D mission has been essentially reactive. As the Corps responded to national needs, it provided WES with the facilities and general direction to resolve technical problems in specific areas. National priorities—and thus Corps priorities—have changed with time. In the 1930s for example, the Corps' primary civil works initiative was the massive Mississippi River and Tributaries (MR&T) Flood Control Project. Early WES studies accordingly dealt with flood control in the Lower Mississippi Valley. By the late 1930s, however, national concerns and WES efforts shifted toward navigation improvement and the design of appurtenant structures for dams. Responding to the shock of World War II, WES altered its focus to concentrate on military projects, such as studies associated with the artificial harbors for the Normandy invasion.

By the 1940s, the Station had established a pattern of adapting to Corps and national needs as they arose and had demonstrated the flexibility to respond quickly. Often, as the WES mission evolved, activities in some areas led to unanticipated growth in others. Soil mechanics (geotechnical) investigations began in the 1930s to supplement hydraulic research, and then matured into a distinct engineering field and major organizational element. Environmental engineering studies originated within a small section of the WES Mobility and Environmental Division in the late 1960s before an explosion of activities in the 1970s led to the establishment of a separate Environmental Laboratory. More recently, with the consolidation of R&D activities into ERDC, the Station continued to develop as an institution, its functions and organizational structure changing to reflect the engineering, economic, and political issues affecting the Corps. Nonetheless, the Corps' original R&D focus was hydraulic research. The history of the R&D mission, therefore, begins with those pioneering efforts.

The Birth of Hydraulic Engineering

Long before the advent of civilization, man attempted to harness water to his use.[1] At least 10,000 years ago, the invention of intentional agriculture, the domestication of livestock, and the rise of the first towns led to a need for irrigation systems, urban water supply, and sewage disposal. Knowledge of the engineering behavior of water became a practical necessity. Indeed, all organized societies have depended to some degree on the effective use and control of water for their survival.

After the emergence of civilizations based on written language and the use of metal tools, engineers in Africa, Asia, Europe, and America made remarkable progress. At least 4,000 years ago, the Egyptians built Lake Moesis to store the waters of the Nile. In China the Emperor Wu constructed great flood control works at about the same time. By the Age of Augustus, aqueducts brought fresh water to the cities of the far-flung Roman empire. Modern engineers marvel at the sophisticated irrigation systems of the Incas.


Roman aqueduct: marvel of ancient engineering


Leonardo da Vinci (1452-1519)

Yet prior to the 16th century, nearly all knowledge of hydraulic engineering was *empirical*: derived from observation and experience and with little if any theoretical or mathematical basis. It was not until the Italian Renaissance that scientists and engineers attempted a quantitative approach. Da Vinci, as a father of hydraulic engineering, compiled nearly 8,000 pages of notes dealing with hydraulic phenomena such as the rate of flow of water through orifices. Italian preeminence in hydraulic studies lasted through the 1600s, when leadership shifted to France. There the Bourbon monarchs provided funding for research. By the 19th century, state-of-the-art developments spread from France to Britain, Germany, and other European nations.[2]

Hydraulic Modeling

In the last quarter of the 19th century a modest number of European engineers began to study hydraulic processes through a revolutionary and controversial method: small-scale modeling of actual rivers and harbors. (The original, full-size natural phenomenon or structure that is reproduced with a model is referred to as the prototype.) Those model studies relied on the Principle of Similitude, first defined by Sir Isaac Newton in 1686. Similitude held that if two geometric figures were drawn so that all corresponding lines were of the same ratio and their corresponding angles were of the same degree, the two figures were similar, and all the properties of one could be determined from the other.[3]

Expanding Newton's concept to include the small-scale reproduction of natural phenomena such as rivers and harbors, engineers theorized that the hydraulic behavior of prototypes could be studied accurately, rapidly, and inexpensively with models. Realizing that reproduction of an exact scale model of such a large and complex entity as a river valley was generally impossible, early model designers noted that a certain amount of distortion was necessary in a model to produce the phenomena occurring in the prototype. For example, a model of a 100-mile river reach built with a horizontal scale of 1:1,000 would be 528 feet long. For a wide but relatively shallow river like the Mississippi, a 1-mile-wide section of the river would be 5.28 feet wide in the model, an easily constructed and functional unit. However, a 50-foot-deep section of river channel at the same ratio would be a mere 0.05 feet (0.6 inches) deep in the model, and could not simulate flows or other conditions. At this scale, shallow areas could not be reproduced in a model at all. Model designers learned to employ a larger vertical than horizontal scale in the same model, and to exaggerate slopes to achieve proper depths and flows. Also, in many cases, materials used in models could not adhere to the principle of geometric similitude. Sand for the bed of a river model with a scale of 1:1,000 would be microscopic. Instituting the concept of hydraulic similitude, engineers thereby subordinated precise model replication of the dimensions of a prototype to the creation of conditions in a model that simulated the empirically determined behavior of the prototype as faithfully as possible.

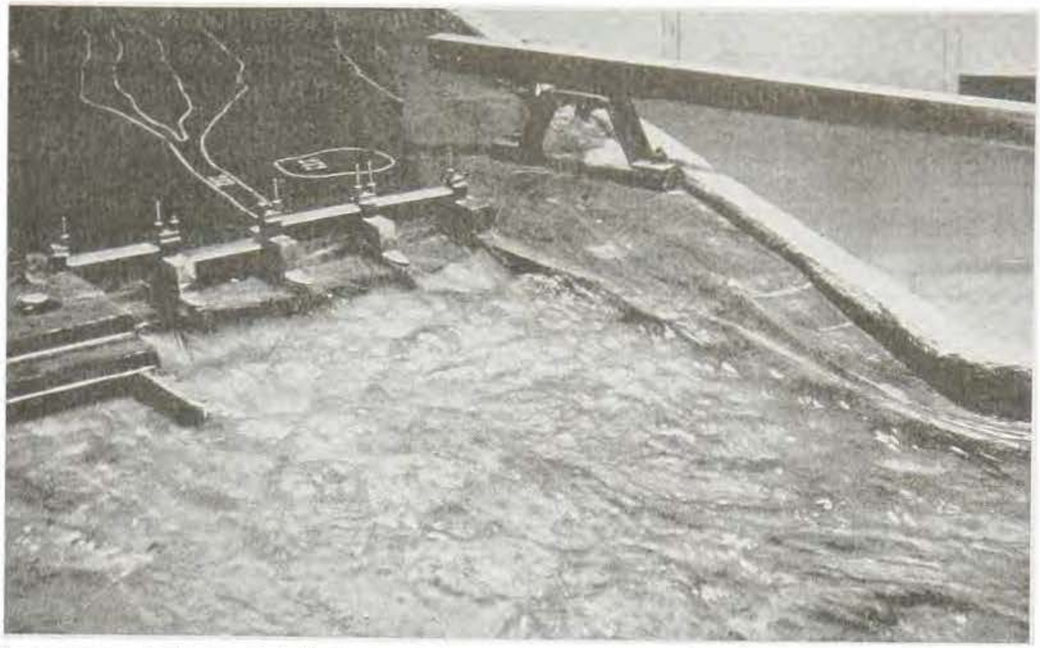
In 1875, Louis Jerome Fargue, a French civil engineer, constructed some of the first true river models. Attempting to improve the channel of the Garonne River for navigation, he devised miniatures with a scale of 1:100. Ten years later, Osborne Reynolds of the University of Manchester, England, used scale models to investigate flows in a tidal estuary of the Mersey River at Liverpool. At about the same time Sir William Vernon-Harcourt attempted to apply the principle of similitude to improve navigation near the mouth of the Seine River in France. Primitive equipment, haphazard planning, and a lack of understanding of the basic principles of model research hampered the efforts of all.

Hubert Engels of the *Technische Hochschule* (Technical University) at Dresden, Germany, launched a new era in river research. In 1891, while touring the United States, Engels found a hydraulic laboratory at the University of Michigan with demonstration equipment used for classroom instruction. He was particularly impressed by use of a glass-sided flume designed to illustrate the flow of water over a weir. On his return to Germany, Engels began experimenting with hydraulic models, and in 1898 built a small laboratory in a university basement. By 1913 he had replaced the original facility with a completely new and much larger river hydraulics laboratory.

Engels' work quickly attracted the attention of other German engineers and institutions. George de Thierry established a hydraulic-modeling laboratory at the *Technische Hochschule* at Berlin in 1903, while Theodor Rehbock headed a similar facility at Karlsruhe. Also in Berlin, Hans-Detlef Krey directed research at the *Versuchsanstalt für Wasserbau und Schiffbau* (Experiment Institute for Hydraulics and Naval Architecture). These and other endeavors placed Germany at the center of hydraulic engineering development prior to World War I.

John R. Freeman

German advances found an avid American proponent in John R. Freeman.[4] A graduate of the Massachusetts Institute of Technology (MIT), in 1913 Freeman toured European hydraulic engineering laboratories, including Engels' at Dresden. Profoundly impressed, he became a powerful lobbyist in the 1920s for the establishment of a national hydraulic laboratory in the United States that would specialize in hydraulic modeling. Terms as president of both the prestigious American Society of Civil Engineers (ASCE) and the American Society of Mechanical Engineers (ASME) gave him a large and influential professional audience. In 1929 he edited *Hydraulic Laboratory Practice*, an enlarged version of a 1926 German publication, providing detailed descriptions of hydraulic research facilities in Europe and the United States, and with copious notes on theories of hydraulic modeling.



Indoor hydraulic dam model, Karlsruhe, Germany

Outdoor hydraulic river model, Dresden, Germany

To further promote the transfer of European knowledge to the United States, he funded three scholarships for American engineers to study in Europe while persuading eminent German engineers such as de Thierry and Rehbock to take temporary assignments as instructors at MIT.[5]

Freeman's arguments in favor of a national hydraulic laboratory met with mixed reactions. Endorsements came from the 42,000-member American Engineer Council, from the Department of the Agriculture's Reclamation Bureau (later Bureau of Reclamation), and from the internationally respected engineer and Secretary of Commerce Herbert C. Hoover. Political support came from Senator Joseph H. Ransdell of Louisiana, a state notoriously prone to flooding from the Mississippi River. In 1924 Ransdell's Senate Commerce Committee passed a resolution to establish a national hydraulic laboratory in the

District of Columbia, but to the dismay of Freeman and the lab's partisans, the measure got no further. The primary reason for the failure of Ransdell's bill was adamant opposition from the Corps of Engineers and from former and current members of the Mississippi River Commission (MRC).[6]

The Corps of Engineers and Flood Control

Since the American Revolution the Corps of Engineers has performed vital services for the U.S. Army and the nation during both war and peace. The Office of the Chief of Engineers (OCE) in Washington, D.C., headed the Corps through most of its history. In the 1980s, the Department of Defense elevated the Office of the Chief of Engineers to command status and changed the appellation of the Corps' administrative headquarters to the more cumbersome Headquarters, U.S. Army Corps of Engineers (HQUSACE).

The Corps' primary field units, responsible for the actual construction, application, and administration of most Corps projects, are its divisions and districts. Corps divisions are based on geographic factors such as drainage basins. Each is headed by a regular Army officer, usually a Brigadier General, with the title Division Engineer. Each division is divided into subordinate districts, also commanded by a regular Army officer with the title District Engineer. The Mississippi Valley Division, for instance, encompasses the Mississippi River Valley from its headwaters at Lake Itasca, Minnesota, to the Gulf of Mexico. Its six districts are:

1. the St. Paul District,
2. the Rock Island District,
3. the St. Louis District,
4. the Memphis District,
5. the Vicksburg District, and
6. the New Orleans District.

The Corps has been involved in river engineering since 1824, when Congress authorized it to improve navigation on the Ohio and Mississippi Rivers by removing snags and eliminating sandbars. This marked the beginning of a Corps presence in the Mississippi Valley that increased through the mid-1800s. By 1879 growing pressures for navigation improvements and flood control measures led Congress to establish the Mississippi River Commission -- an agency charged with developing and executing a comprehensive plan for flood control and navigation works on the Mississippi River. Originally headquartered in St. Louis, now in Vicksburg, the MRC includes three members from the Corps of Engineers (with one serving as president of the commission), one member from the U.S. Coast and Geodetic Survey, and three civilians, two of which must be civil engineers. In its initial report to Congress, the MRC recommended levees as the most practical and economical line of defense against floods on the Mississippi River, a policy that devolved into a

Corps of Engineers Divisions

Mississippi Valley Division and subordinate districts

reliance on a "levees-only" approach to flood control. In 1882, Congress authorized the MRC to supervise the building of levees as aids to navigation, but strictly prohibited the commission from building levees solely for the purpose of protecting adjacent lands from overflow. Nevertheless, levee construction consumed most of the energies of the MRC and the Corps on the lower Mississippi River for the next five decades.[7]

By the 1920s — as Freeman and his allies attempted to establish a national hydraulic laboratory — the Corps had developed an expertise in river engineering based on practical experience and field operations without the use of hydraulic models. Convinced that its "levees-only" policy would succeed in controlling flooding on the Mississippi, Corps leaders and MRC members were reluctant to endorse innovations about which they had little direct knowledge and that they considered unnecessary. During committee hearings before Congress, Corps and MRC personnel were quick to express their reservations about hydraulic modeling and the need for a hydraulic laboratory. Congress listened intently. Thus after the failure of Ransdell's 1924 bill and despite renewed efforts by Freeman, the establishment of any type of federally-sponsored hydraulic laboratory appeared unlikely. Then, disaster intervened.

The 1927 Flood

The monumental Mississippi River flood of 1927 might well have affected public policy more than any other natural disaster in American history. Causing the deaths of over 300 people, displacing 637,000 others, and inflicting more than $1 billion in property damages (adjusted for inflation since then), the "superflood" awakened the nation to the need for a more diligent flood control effort. Shocked into action, Congress passed the Flood Control Act of 1928, committing the Federal government to a full-scale flood prevention program in the Mississippi Valley and, in vague terms, authorizing the Chief of Engineers to take "whatever steps that were necessary" for effective flood control. The flood also revived interest in establishing a national hydraulic laboratory.[8]

Victims of the 1927 Mississippi River flood seek refuge on a levee

1927 Mississippi River flood

From an engineering standpoint, the flood demonstrated the complete inadequacy of the federally mandated "levees-only" policy for controlling the Mississippi River. In 1928, Chief of Engineers Major General Edgar Jadwin obligated the Corps to a more diverse program of river control that eventually involved floodways, channel stabilization, reservoir construction on tributaries, coordinated plans for levee construction, and river cutoffs. Although previously opposed to the idea of a hydraulic laboratory, Jadwin, in congressional hearings in 1928, called for establishment of such a facility under the Corps' jurisdiction, somewhere along the Mississippi River. Much of Jadwin's change of heart was political, as he feared Congress would authorize a national laboratory located in Washington, D.C., administered by the Bureau of Standards, depriving the Corps of control of hydraulic research. Freeman and his associates, in fact, vehemently argued that such a laboratory be under civilian control and not be administered by the Corps.[9]

In the meantime, hydraulic research efforts, including some that involved modeling, had grown steadily in the United States. In 1922, nearly 40 academic institutions claimed some experimental hydraulic facilities used almost exclusively for instructional purposes. Two Federal agencies, the Department of Agriculture's Reclamation Bureau and the Bureau of Standards also had small research facilities. The former, at Fort Collins, Colorado, dealt with dam and irrigation projects while the latter consisted of a single rating tank in Washington, D.C.[10] By 1928 there were more than 50 hydraulic laboratories in the U.S. and Canada, most still academic. Only three, the laboratories at Cornell University, Iowa University, and at the Worchester Polytechnic Institute, were of appreciable size.[11]

Establishment of WES

Major General Edgar Jadwin, Chief of Engineers, 1926-1929

In 1929, while Congress resumed the debate over whether to establish a national laboratory, Jadwin acted. Taking the wording of the Flood Control Act at face value, he indicated that a hydraulic laboratory, under Corps

Mississippi River Commission building, Vicksburg

control, was now a necessity and on 18 June 1929 directed Brigadier General Thomas H. Jackson, the MRC President, to establish such a facility at or near Memphis, Tennessee. However, Jadwin's instructions that it "be constructed gradually as information develops as to the needs of such a laboratory," and his opinion that "Experiments at the laboratory itself may be needed continuously or intermittently" hardly rang of urgency and further reflected the Corps' tepid interest in hydraulic modeling.[12]

On 16 November 1929, as preparations sluggishly progressed to select a site and devise construction plans for a laboratory in Memphis, Major General Lytle Brown, Jadwin's successor as Chief of Engineers, suddenly ordered that all work cease in Memphis and that operations be transferred to Vicksburg. Because the Corps had decided to relocate the headquarters of the Mississippi River Commission from St. Louis to Vicksburg, Brown was of the opinion that it would be advantageous for the MRC and the planned hydraulic laboratory to be in close proximity.

Major General Lytle Brown, Chief of Engineers, 1929-1933

Furthermore, the MRC president would become *ex officio* Division Engineer of the Corps' Lower Mississippi Valley Division (LMVD), also to be headquartered in Vicksburg. The city was thus to become headquarters of four interrelated entities engaged in flood control and river engineering: the MRC, the LMVD, its Vicksburg District, and soon, the Corps' laboratory.

Brown, anticipating that the laboratory's work would be concentrated on the Lower Mississippi River, placed it under the administrative jurisdiction of the MRC. This created a peculiar situation in that the president of the MRC, who was also the LMVD Division Engineer, was nominal laboratory chief. Unless orders came directly from the Chief of Engineers, the MRC president initiated or approved work performed by the laboratory. This arrangement lasted until 1949.

Brown chose to name the nascent facility the U.S. Waterways Experiment Station. To avoid any implication of association with a proposed national hydraulic laboratory, and to mollify such a laboratory's supporters, there was no use of the terms Corps of Engineers, hydraulic, research, or laboratory.[13]

Ironically, in the spring of 1930 — while the Corps' hydraulics laboratory began to take shape in Vicksburg — Congress authorized establishment of a National Hydraulic Laboratory in Washington, D.C., under the Bureau of Standards. Freeman, the national laboratory's chief advocate, had already prepared extensive designs for a building and its major equipment. Thus, not one but two federally mandated research facilities began operation in the same year: the obscure Waterways Experiment Station at Vicksburg, largely political in origin and with few advocates; and the National Hydraulic Laboratory in Washington, D.C., that had the active support of Freeman, most of the civilian engineering community, and President Herbert Hoover. Few, if any, could have foreseen that the former would

evolve into the world's premier research institution in hydraulics engineering, while the latter never exercised more than a minimal influence.

Herbert D. Vogel

In establishing its Vicksburg facility, the Corps was fortunate to have the services of Lieutenant Herbert D. Vogel.[14] A Michigan native, Vogel graduated from the U.S. Military Academy in 1924, completed several assignments, then enrolled at the University of California at Berkeley. There he received a master's degree in civil engineering in 1928. Shortly after graduation, Vogel applied to the Corps of Engineers for assignment in Europe to study German hydraulic engineering techniques. Jadwin had already sent two Army engineers — Colonel E.M. Markham and Lieutenant John Paul Dean — to Europe that year, and he readily approved Vogel's application. Vogel forthwith enrolled as an audit student at the *Technische Hochschule* in Berlin, although he spent substantial time at the nearby *Versuchsanstalt für Wasserbau und Schiffbau* and visited other facilities such as the hydraulic laboratory at Obernach. Despite being only marginally proficient in German, he elected to pursue a doctorate, enrolled in a graduate program, and wrote a dissertation dealing with the effects of deforestation on flood control. The *Technische Hochschule* granted him a degree in 1929.


Brigadier General Thomas Jackson, MRC President, 1929-1932

Vogel returned to the United States in September 1929 and almost immediately was sent to Memphis to oversee the establishment of Jadwin's proposed hydraulics laboratory. Only 29 years old and with only the rank of lieutenant, he was nonetheless one of the Corps' few engineers with firsthand knowledge of European modeling techniques. In Memphis, Vogel began making plans for the location and construction of a laboratory. After only two weeks he received Brown's order to relocate to Vicksburg. Knowing nothing of the Vicksburg area, he asked a Corps secretary for information. Her succinct response was that she had been there once and only remembered it as "a long dusty ride with a cemetery at the end."[15]

Vogel forthwith proceeded to Vicksburg, where members of the MRC were arriving from St. Louis. Lacking office space in Vicksburg for even an administrative headquarters, the MRC for a time operated from quarterboats.[16] Vogel quickly found a staunch and generous ally in Jackson, the MRC president. Also taking the Corps' mandate to "do anything necessary" literally, Jackson granted Vogel virtual *carte blanche* to establish a research facility, including the authority to write his own travel orders.


Lieutenant Herbert D. Vogel, second from right, as a Freeman Scholar in Germany

Vogel enthusiastically tended to the lab's site selection and building design. After reconnoitering the Vicksburg vicinity for a few weeks, he recommended a 147-acre tract about four miles south of the city on Durden Creek. The Secretary of War approved its purchase in February 1930. There, through the spring and summer of 1930, Vogel supervised the construction of a lake and headquarters building while simultaneously authoring the Station's first publication — a review of sediment investigations on the Mississippi River and its tributaries.[17]

With Jadwin's directive to build a facility "gradually as information develops" fading into memory, by the end of 1930, research at WES had begun.

Notes

1. "Hydraulics" in its full sense included the study of the behavior of other fluids of low viscosity in addition to water. For this study the term is restricted to the engineering behavior of water.

2. The early evolution of hydraulic engineering is chronicled in Hunter Rouse and Simon Ince, *History of Hydraulics* (State University of Iowa: Iowa Institute of Hydraulic Research, 1957).

3. An excellent discussion of early attempts at hydraulic modeling and the principle of similitude is included in Herbert D. Vogel, "Practical River Laboratory Hydraulics," *Transactions of the American Society of Civil Engineers* 100 (1935): 118-84.

4. A highly detailed account of John R. Freeman's role in promoting the establishment of a hydraulic laboratory in the United States is included in Lee F. Pendergrass and Bonnie B. Pendergrass, "Mimicking Waterways, Harbors, and Estuaries: A Scholarly History of the Corps of Engineers Hydraulics Laboratory at WES, 1929 to the Present," (Unpublished manuscript, 1989), WES Archives.

5. A broader study of Freeman's posture in the American engineering community is contained in Hunter Rouse, "John R. Freeman's Influence," Chapter V in *Hydraulics in the United States, 1776-1976* (State University of Iowa: Institute of Hydraulic Research, 1976), 102-24.

6. See Arthur E. Morgan, "Opposition of the Corps of Engineers to the Hydraulic Laboratory," Chapter 7 in *Dams and Other Disasters: A History of the U.S. Army Corps of Engineers in Civil Works* (Boston: Porter Sargent Publisher, 1971), 185-239, for a full, and highly vitriolic discussion of the Corps' role in preventing the establishment of a national laboratory.

7. See Charles A. Camillo and Matthew T. Pearcy, *Upon Their Shoulders: A History of the Mississippi River Commission from its inception through the advent of the modern Mississippi River Tributaries Project,* (Vicksburg, Mississippi River Commission, 2004).

8. A detailed account of the 1927 flood and its aftermath is included in John M. Barry, *Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America* (New York: Simon and Schuster, 1997). Barry particularly chronicles the political impact of the great flood and the role, in an unflattering fashion, of the Corps of Engineers. Another highly readable account is Pete Daniel, *Deep'n as it Come: The 1927 Mississippi River Flood* (New York: Oxford University Press, 1977).

9.Camillo and Pearcy, *Upon Their Shoulders*.

10. Rouse and Ince, 97.

11. See *Twenty Years of Bureau of Reclamation Hydraulic Laboratory Practice. A Paper for the Summer Convention, ASCE, Denver, Colorado, June 1952* (Denver: Bureau of Reclamation, 1952).

12. Detailed accounts of the background and establishment of the Waterways Experiment Station are included in Pendergrass, "Mimicking Rivers"; Joseph B. Tiffany, ed., *History of the Waterways Experiment Station* (Vicksburg: WES, 1968); and Gordon Cotton, *A History of the Waterways Experiment Station* (Vicksburg: WES, 1979). WES celebrates its "official" birthday as 18 June 1929.

13. Vogel left numerous accounts of his role in the founding and early history of WES. Among them are Herbert D. Vogel, "The U.S. Waterways Experiment Station," *The Military Engineer* 23 (1931) No. 128, 152-53; Herbert D. Vogel, "Research at the Waterways Experiment Station," *The Military Engineer* 24 (1932) No. 136, 331-35; Herbert D. Vogel, "Origins of the Waterways Experiment Station," *The Military Engineer* 53 (1961) No. 352, 132-35; Herbert D. Vogel, "Conception, Birth, and Development of the U.S. Waterways Experiment Station," (unpublished monograph), Record Collections, Office of History, HQ, USACE, Kingman Building, Fort Belvoir, Virginia, General Files, Box 123, Folder 6. Further details are provided in Herbert D. Vogel, interview by Michael C. Robinson, Vicksburg, 14-15 June 1984, typed transcript in WES Archives; and Herbert D. Vogel, interview by Sue Ellen Hoy, Public Works Historical Society for the Historical Division, U.S. Army Corps of Engineers, Washington, D.C., November and December 1976.

14. Herbert D. Vogel, *Sediment Investigations on the Mississippi River and its Tributaries Prior to 1930. Paper H of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1930).

15. Herbert D. Vogel interview by Michael C. Robinson.

16. Camillo and Pearcy, *Upon Their Shoulders*, 178.

17. Herbert D. Vogel, *Sediment Investigations on the Mississippi River*.

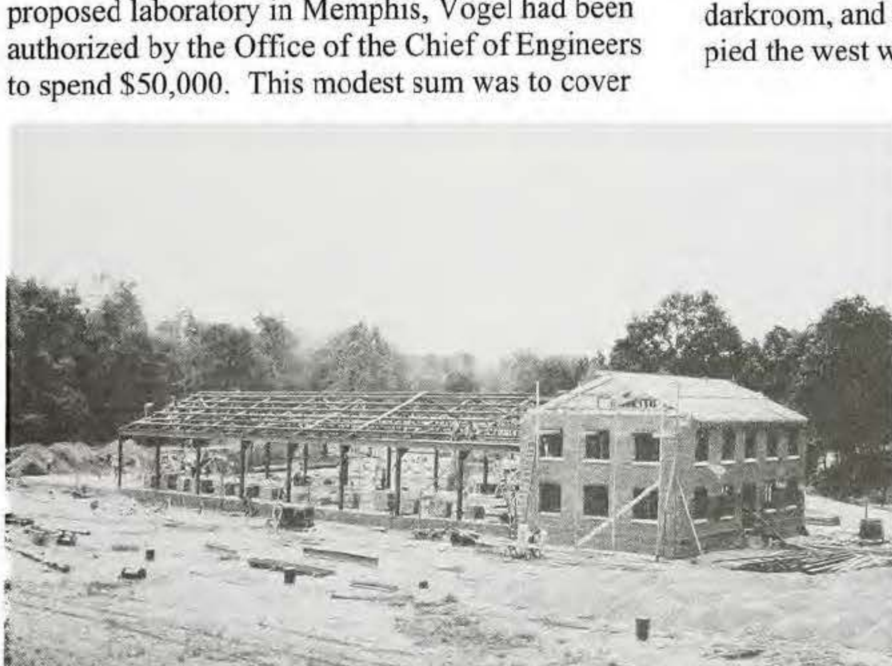
2 The Vogel Years, 1930-1934

Facilities and Equipment


Lieutenant Herbert D. Vogel

In building WES literally from the ground up, Vogel faced four challenges: constructing adequate facilities, acquiring proper equipment, hiring competent personnel, and attracting sponsors for projects. In meeting each of these, he was extraordinarily successful.

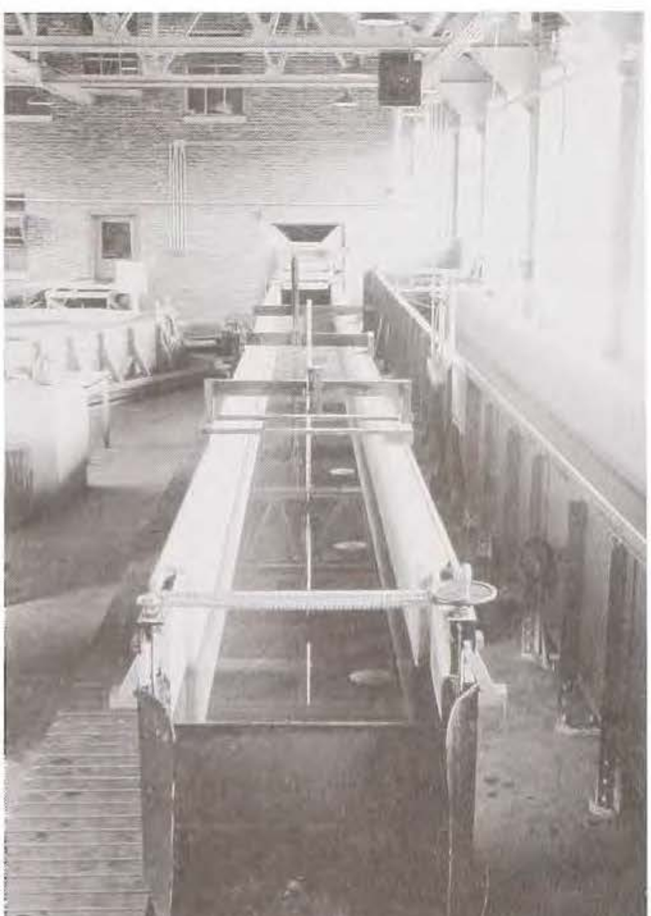
While outlining plans for the original proposed laboratory in Memphis, Vogel had been authorized by the Office of the Chief of Engineers to spend \$50,000. This modest sum was to cover Vogel's salary in addition to the construction of a World War I-type building of "elephant iron." In Vicksburg, however, with the solid backing of General Jackson and the Mississippi River Commission, Vogel later estimated he had spent nearly \$1 million in the Station's first year. Upon completion in November 1930, the brick main building alone cost \$122,000, with Jackson providing the necessary approval. The building consisted of an open, high-ceiling experiment hall flanked on both ends by two-story wings. The main hall was long enough to house a 165-foot-long flume, small movable models, and other laboratory equipment. Not partitioned from the main hall, the east wing served as a pump room with enough open space to allow the assembly and disassembly of movable models. Three offices, a calculating and drafting room, a carpenter shop, a darkroom, and a sediment-reduction room occupied the west wing.[1]


Construction of main WES building, 1930

Because hydraulics experiments required a large and stable water supply, Vogel supervised construction of a dam immediately behind the headquarters building. Completed in mid-October 1930, the earthen structure soon held a 40-acre lake that Vogel named after Major General Brown, who gave the order to move the project from Memphis to Vicksburg. The lake provided water directly to the main building and to the large open area in front of the building through conduits. A pumping system insured that water could be transferred from the lake even

Completed main building

Brown's Lake and Vogel's home



Early indoor WES flume

during droughts, although this later proved inadequate in extreme conditions.[2]

Vogel acquired commercial equipment from various sources when available, including pumps, gages, and laboratory experimental equipment. However, much of the gear, especially larger apparatuses, such as holding tanks, flumes, weirs, and traps inside the main building, had to be designed and built on the premises. In cases where equipment was entirely lacking or ineffective, WES personnel quickly developed the expertise to devise and manufacture new types. Two factors made this possible: practical construction skills developed through experience, and the uninhibited ability of WES engineers to apply innovative ideas to distinctively American conditions. In the latter, WES from its birth was a pacesetting institution in hydraulics engineering. When European prototype conditions failed to match those in the United States — particularly the presence in North America of large, meandering, alluvial rivers with complex beds and basins — WES designed and built new structures on scales unheard of in Europe. In its first year of operation, the Station's Yazoo Basin backwater model was the largest in the world. WES also soon led the engineering world in the use of exaggerated model distortion.[3]

Recruiting Personnel

Recruiting quality personnel proved arduous but surprisingly rewarding. Hydraulics specialists were inherently difficult to locate in the best of

Early bed load sampler

James G. Jobes, one of first WES civilian engineers

civil service appointments. The Vicksburg District assigned three junior engineers to WES — James G. Jobes, a graduate of the University of Michigan; Georgia Tech alumnus William Willingham Woods; and Isham H. Patty, who was actually a pharmacist by education. Resorting to unconventional methods, Vogel took advantage of Jackson's license to write his own travel orders and visited MIT, the University of Michigan, the University of Illinois, the University of Iowa, and other institutions engaged in hydraulics research. At each he attempted to recruit personnel for the Station, offering to hire their top graduates as "laborers" at $100 per month with 15 percent deducted. Since jobs were at a premium at any wage, a number of highly-qualified and capable young men who might not have been available in better times accepted Vogel's offer "with alacrity." University of Illinois graduates Joseph B. "Joe" Tiffany and Frederick R. "Fred" Brown, for example, came to WES in 1933 and 1934 respectively, then remained to achieve lengthy and distinguished careers as researchers and administrators. Tiffany had been valedictorian of the Illini class of 1932. Vicksburg native John J. Franco, an electrical engineering graduate of Mississippi State College (later Mississippi State University), began his stellar 40-year WES career in 1933 as a gage reader.[4] Vogel also persuaded OCE to allow lieutenants pursuing post-graduate studies to "intern" at WES. Through this program he attracted Lieutenant Francis H. Falkner and Lieutenant Paul W. Thompson, a former Freeman Scholar, both of whom succeeded Vogel as WES Director. Vogel referred to his hand-picked, professional-grade cadre as "brilliant engineers" with no lifetime theories to uphold, any of whom "would have been glad to prove Sir Isaac Newton wrong."[5] As an added attraction, most were single men, a fact that Fred Brown modestly claimed provided a "great boon to the young ladies of Vicksburg."[6]

Vogel's successors, including Falkner, continued his hiring practices, in some cases with stunning results. Upon graduating with a degree in engineering from the University of California at Berkeley in May 1935, future hydraulics pioneer and Corps of Engineers administrator Jacob H. Douma found himself in the envious position of having two job offers, one from the fledgling Tennessee Valley Authority (TVA), the other from the almost equally nascent Waterways Experiment Station. The former position paid $105.00 per month, the latter $110.00. Douma chose WES for the five dollars more. Upon arriving in Vicksburg, Douma received an unexpected boost to $120.00 per month with the high-sounding grade of gauge reader pro-tem.[7]

Within a year, Vogel had assembled a civilian staff of about 20, including four professional engineers, eight sub-professional engineers, one clerk, two skilled workmen, and six laborers. By mid-1932 the total had increased to 34, then, as Station activities burgeoned, to 185 in 1933, 215 in 1934, and 401 in 1935. Of that latter number, 16 were professional engineers and 103 sub-professional engineers, while the number of laborers had surged to 236. As previously stated, some of the "laborers" were actually engineers by education. (Numbers for 1935 were inflated due to construction of the huge Mississippi River Flood Control Model, discussed in Chapter 3). Surveyors, draftsmen, photographers, and other trained specialists complemented the diverse work force.[8]

Joseph B. Tiffany surveys the 1937 Mississippi River flood

Civilian Personnel Employed at WES, 1931-1935					
Classification	Number Employed at End of Fiscal Year				
	1931	1932	1933	1934	1935
Professional Engineers	4	6	7	9	16
Sub-Professional Engineers	8	10	52	66	103
Clerks	1	2	4	7	9
Tradesmen & Skilled Workmen	2	4	11	14	37
Laborers	6	12	111	119	236
Totals	21	34	185	215	401

Organizational Evolution

Vogel instituted the first simple laboratory organization in January 1931, shortly after the beginning of experimental work. This consisted of three laboratory groups with a single group coordinator in general charge of all activities. The Hydraulic group dealt with fixed-bed models, the Sediment group worked only with movable-bed models, and the Soils group performed supporting studies. (Fixed-bed and movable-bed models are discussed later in this chapter.) By October 1932 the volume and diversity of work had expanded beyond the capabilities of the group coordinator, leading Vogel to abolish the group structure and establish two independent hydraulic sections. These handled fixed- and movable-bed models, respectively. The leader of each section was responsible for all design, construction, and operation of each of his models, and at the same time carried on all correspondence and wrote reports. This arrangement lasted only until January 1933.[9]

The real functional subdivision of WES began in January 1933 when Vogel set up three sections with separate, though interrelated, functions:

- Research and Experimentation,
- Construction, and
- Administration and Reports.

The Research and Experimentation Section conducted technical research and gathered data. It in turn consisted of four groups, one each for fixed-bed models, movable-bed models, tidal models, and soils laboratory work. To free the Research and Experimentation Section from the burden of construction details, Vogel established a Construction Section as a service unit, while a new Administration and Reports Section provided clerical and drafting services.

Only a few months later, in September 1933, Vogel initiated yet another structural overhaul. Retaining a three-unit format, he entitled the new sections:

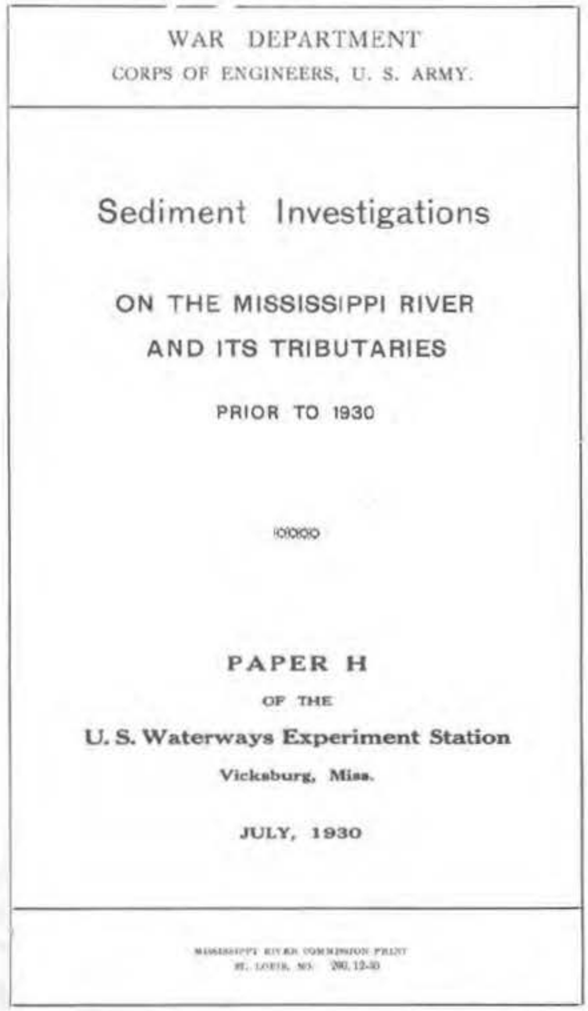
- Experiment,
- Research and Publications, and
- Operations

The Experiment Section, headed by Patty, had complete control over design and operation of models. Within it, three groups specialized in particular model types: Group 1 under Jobes and later James B. Leslie dealt with fixed-bed models; Group 2 under Robert B. Cochrane with movable-bed models; and Group 3 under Henry Sargent with tidal models. Each had from three to six subgroup leaders and was charged with from six to 12 projects at any given time. Tiffany headed the new Research and Publications Section, which conducted technical experimental research and edited reports that were to be published. All service functions fell to the Operations Section, including construction, administration, and the soils laboratory. However, the soils laboratory soon left the Operations Section to form Group 4 of the Experiment Section.[10] This structure lasted until November 1935, more than one year after Vogel left WES.

First WES Projects: Sedimentation Studies

Research and publication began at WES even before completion of the dam and main building, although not with hydraulic models. The MRC had for decades gathered sedimentation data from the Mississippi River and its tributaries. On orders from the MRC president, Vogel compiled and examined these records. In July 1930 he completed the first WES paper, published by the MRC as *Sediment Investigations on the Mississippi River and its Tributaries Prior to 1930. Paper H of the U.S. Waterways Experiment Station.* Vogel cleverly labelled this first WES effort as "*Paper H.*" Subsequent publications were, in order, papers "*Y*," "*D*," "*R*," "*A*," "*U*," "*L*," "*I*," and "*C*."

Shortly after the publication of *Paper H*, the MRC ordered Vogel to coordinate a new investigation to project the rate of silting in proposed flood control reservoirs and to add to the fund of data concerning the movement of sedimentary material through the entire Mississippi River system. Personnel from the four districts of the Lower Mississippi Valley Division took periodic sediment trap samples at three river depths — surface, mid-depth, and bottom. Samples came from 26 locations on the Mississippi River and its major tributaries and outlets, including the Missouri, Ohio, Old, Arkansas, Yazoo, Ouachita, Red, and Atchafalaya rivers. Preserved in special containers and mailed to WES, the first samples arrived in late August 1930. The WES sediment reduction laboratory, housed in the west wing of the still-unfinished main building, ran tests to analyze sediment compositions and volumes.



WAR DEPARTMENT

CORPS OF ENGINEERS, U. S. ARMY.

Sediment Investigations

ON THE MISSISSIPPI RIVER

AND ITS TRIBUTARIES

PRIOR TO 1930

PAPER H

OF THE

U. S. Waterways Experiment Station

Vicksburg, Miss.

JULY, 1930

Cover of *Paper H*, first WES publication

River sediment sampler

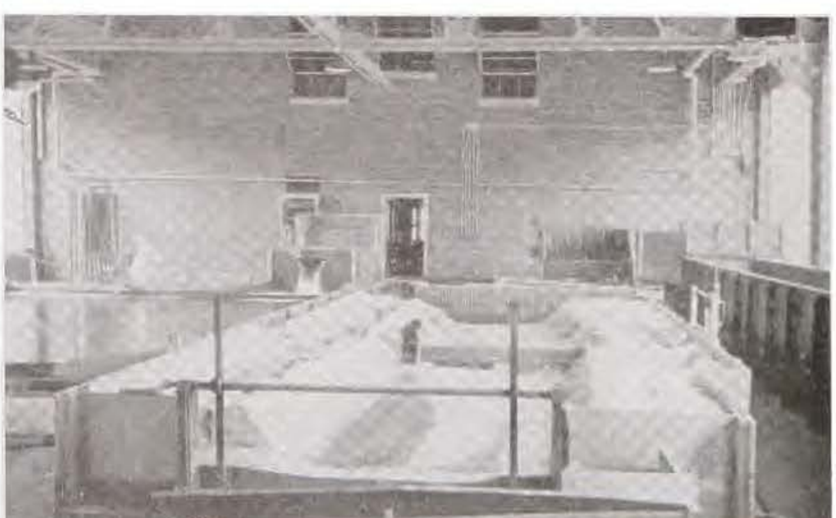
Small current meter

Upon completion of the project in September 1931, the influential *Engineering News-Record* called it "the most systematic and complete" study of its type ever performed.[11]

First WES Models: Ohio River Lock and Dam

WES model tests began at the end of 1930. (These were not the first conducted by the Corps. The St. Paul District's suboffice at Iowa University had conducted model tests for Hastings Dam, on the Upper Mississippi River, in 1929 and 1930.[12]) On 27 October 1930, only two weeks after completion of the WES dam, the Cincinnati District Engineer requested through the MRC that WES perform a study of a section of the Ohio River where the proposed Lock and Dam No. 37 complex was to be redesigned. Amid noticeable excitement, construction of the first two indoor WES models began on 3 December. Located in the main hall of the headquarters building, one represented a 4,000-foot section of the Ohio River with a 1:300 horizontal scale and a 1:60 vertical scale. This produced a 5:1 distortion, since the horizontal ratio was five times that of the vertical (300:60). The other model, which was undistorted, reproduced a smaller river reach. Following European techniques, workmen built both by cutting templates of galvanized iron to conform with cross-sections of soundings along the river reach, then spaced the templates less than one foot apart inside a simple lumber-framed box 30 feet long, 12 feet wide, and 2 feet deep. Crews molded sand into the spaces between the templates up to about an inch below the top edges of the templates and then carefully troweled a cement surface to the level of the templates. This yielded a fixed-bed solid contour of the river bottom.[13]

After completion of the model river sections, replicas of the existing dam and its appurtenant structures were added. These could be altered or remodeled in various fashions to determine the effects of revisions in the prototype. Project personnel then introduced water flow into the models and made adjustments until the flow patterns in the model corresponded to the empirically determined patterns of the prototype. The models were then considered verified. Experiments could be performed on a number of alternate dam and lock designs, each subjected to different river levels, including maximum flood



First WES indoor model, Ohio River Lock and Dam No. 37, December 1930

stage. Following several weeks of tests — final observations were not made until 15 May 1931 — a WES report furnished detailed recommendations for use by the Cincinnati District in its choice of dam alterations.[14] However, before action could be taken, a directive from OCE called for the Ohio River Division to restudy its entire canalization program on the Ohio River. The Cincinnati District then suspended plans for improving existing dams.

First Outdoor Model: Illinois River Backwater

In late December 1930 the Station began its first experiments with an outdoor model. The Chicago District Engineer requested a model study of the Illinois River to determine the limit of the river's backwater — the maximum distance that the river would back up from its mouth in times of flooding. Flowing across the fertile farmland of central Illinois and emptying into the Mississippi River just north of St. Louis, the Illinois presented the Corps with an important flood control challenge. By defining the limit of the river's backwater, the Corps could design a levee system to protect the entire area from inundation. Accurate calculation would not only insure that levees extended far enough upriver to check flooding, but would save a great deal of money by avoiding unnecessary construction above that point. The project had a degree of urgency because the Chicago District needed data within 30 days to make recommendations to Congress.[15]

In the Illinois River project, WES demonstrated that American researchers were capable of exploring new channels in large-scale modeling. This was necessary because river conditions in the United States often differed materially from those in Europe, both in size and complexity. No European river, for example, rivals the Mississippi in length, volume, or meandering tendencies. Even the Illinois River is large by Western European standards. With this in mind, Vogel and other Americans who had studied in Europe felt that models of rivers at home must have greater dimensions and more distortion than their European counterparts, a concept most European engineers questioned.

First WES outdoor model, Illinois River backwater, January 1931

The Illinois River project posed an immediate challenge. Because a reliable model would be much too large for the WES building, Vogel ordered it constructed outdoors. European river modeling practices called for design and construction of a concrete fixed-bed model, but this was impossible in the short time allotted. According to Vogel, he and Clarence Bardsley resorted to innovative but simple techniques. Bardsley, a Freeman Scholar in 1928 and 1929, had taken a leave from the faculty of the Missouri School of Mines for a short-term job at WES. Acting on the assumption that a reliable model could be carved directly into the loess soil of the Station's grounds, WES workmen began digging into a flat area stretching from the headquarters building south toward a highway. Using topographical maps as a guide, Bardsley had templates cut from steel sheets and fitted to the ground to trace the river's channel. Crews then simply dug into the soil, carving out channels to depths determined by soundings of the prototype as marked by the template. After completion of the model's channels, miniature overbank structures were added — first the existing levees, then additional levees proposed by the Chicago District.[16]

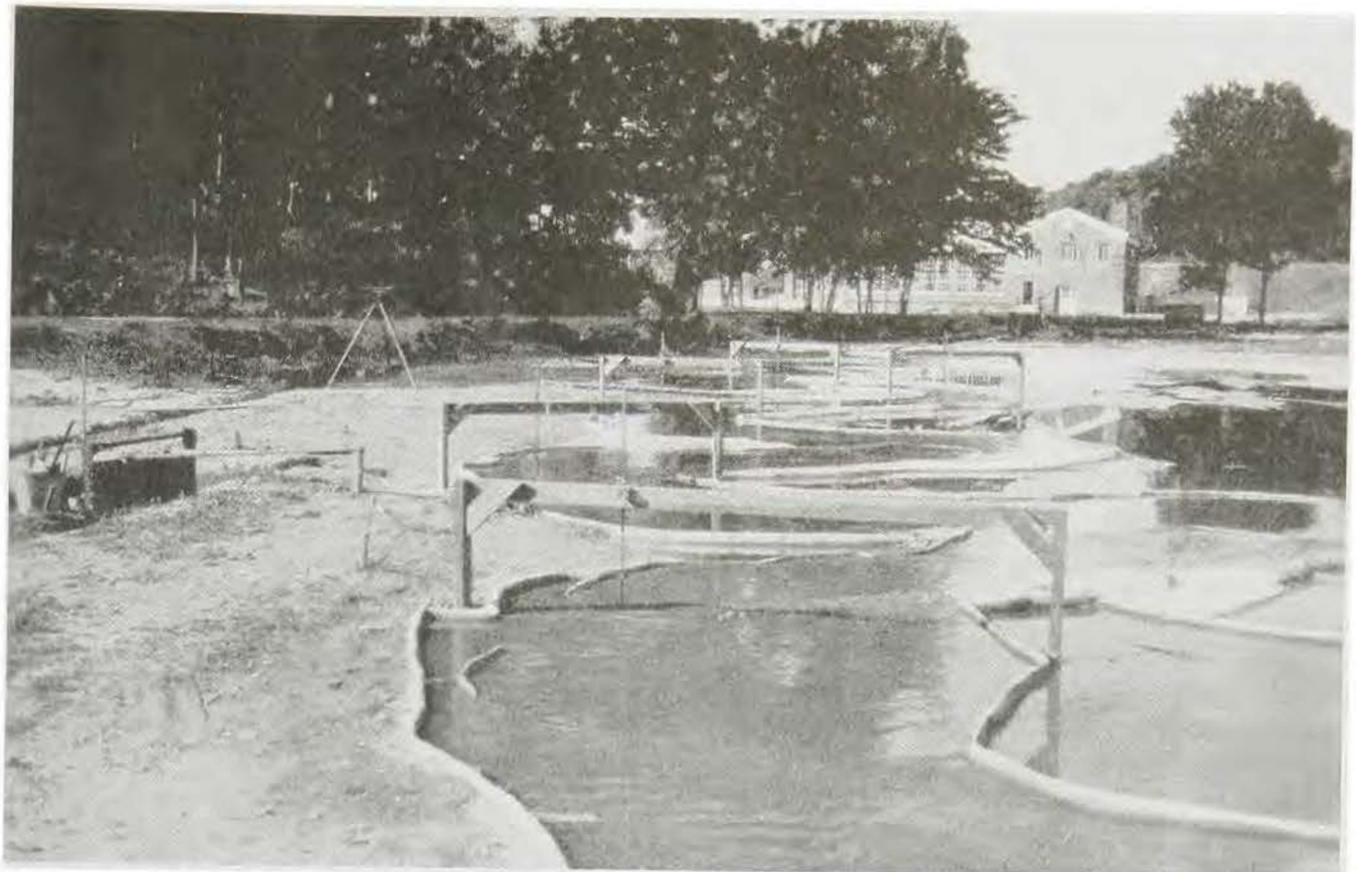
The model deviated radically from its European progenitors. Neither European publications of the time nor Freeman's *Hydraulic Laboratory Practice* suggested that models could be dug into the ground. Also, the mere size, the ratios, and the distortion the model incorporated were revolutionary. At nearly 600 feet in length, Vogel claimed that his creation was the largest hydraulic model in the world. While European engineers considered a horizontal scale of 1:300 to be large, the Illinois River model's scale was 1:1,200. Its vertical scale of 1:48 produced a 25:1 distortion, a ratio also unused in Europe but necessary to reproduce conditions in so large a prototype as the Illinois River.[17]

To calculate the Illinois' backwater limit, Vogel used the model to replicate several scenarios. The final and most crucial experiment involved simulating the maximum known historical flood flow of the Illinois with the maximum known flood stage of the Mississippi River at its confluence with the Illinois. This was accomplished by allowing a proportionate measured volume of water into the model at its source. Also, a weir was placed at the end of the model (which represented the confluence of the Illinois and Mississippi Rivers) and raised to represent flood levels on the Mississippi. Since the Mississippi at flood stage would cause the Illinois to back up in even normal conditions, the combination of simultaneous floods on both rivers would produce the maximum backwater influence on the Illinois.[18]

Results from the experiments indicated that the limit of backwater from the Illinois was about 120 miles up from the river's mouth. According to Vogel, Congress established the mark as the the Illinois' backwater limit, enabling the Corps to complete its levee program with a degree of confidence and at minimal cost. After the recording and reporting of data, the model was demolished to clear space for another.[19]

Yazoo Backwater Project

WES had scarcely finished the Illinois River backwater project when in March 1931 the MRC requested a similar investigation of the Yazoo River Basin. Forming the eastern border of the verdant Mississippi Delta, the Yazoo and its numerous tributaries form a large basin susceptible to flooding. Like the Illinois, the Yazoo flows into the Mississippi, which, when at flood stage, produces an extensive backwater up the Yazoo. In the great 1927 flood, still fresh in most memories, the Yazoo had at one time actually run backward up its channel due to the extreme stages on the Mississippi. By 1931, MRC plans called for extending levees on the Mississippi just north of Vicksburg. Since raising the level of the Mississippi at flood stage would affect the Yazoo River backwater limits and retain water in the Yazoo Basin, the MRC called on WES to determine the new Yazoo backwater limits under several scenarios.[20]


Yazoo River Basin backwater model

The Yazoo study led to construction of a model even bigger than its Illinois River predecessor. Stretching over a 13,000-square-foot area in front of the headquarters building, the new project miniaturized a 125-mile stretch of the Mississippi River adjacent to the Yazoo Basin along with the entire Yazoo backwater area. Unlike the Illinois model, when construction time was severely limited, the Yazoo model was a fixed-bed concrete structure. This made long-term, multiple-experiment use possible. It also eliminated excessive seepage and drainage, phenomena that experience with the Illinois River model indicated were out of proportion to similar effects occurring in nature. As with the indoor Ohio River models, skilled technicians cut sheet metal templates to reproduce the rivers' contours, set the templates on a prepared base, filled spaces with sand, and covered the structure with concrete. The concrete surface, left purposefully unfinished to produce overbank roughness, was quite similar in net effect to the natural surface within the area considered.[21]

The Cutoff Controversy

While performing studies of the Ohio River dam site and the Illinois and Yazoo backwaters, WES became embroiled in a long-term investigation of an old and controversial issue: the effects and desirability of cutoffs on the Mississippi River. As an alluvial, meandering stream, the Lower Mississippi forges a serpentine course from the mouth of the Ohio to the Gulf of Mexico. Historically, this course changed continuously, sometimes quickly and dramatically, as the river cut new channels and abandoned old ones. Natural changes occurred most commonly at bends where the river tended to widen a bend further and further until it formed a loop with a narrow neck. Eventually the river cut a shorter channel across the neck, usually at very high water stages, abandoning the former channel, leaving it to form an oxbow lake or fill with silt. The process then began anew.

Corps studies indicated that cutoffs occurred at the rate of about 13 to 15 per century, each shortening the river's length from approximately

six to over 20 miles. But since the river habitually began to lengthen its channel, repeating the cycle after any natural cutoff, the total length of the river from Cairo to Baton Rouge, Louisiana, remained almost unchanged from the early 1800s to the 1930s. Cutoffs did not occur below Baton Rouge.

Some cutoffs were manmade. In 1831, Henry Shreve, river boat captain and founder of Shreveport, Louisiana, ordered a channel dug across the narrow neck of Turnbull's Bend, about 80 miles above Baton Rouge.[22] Shortening the river notably pleased river boatmen and other commercial interests, but the long-term repercussions of tampering with the river's natural course remained unknown.

From the mid-1800s until the 1930s the Corps and the MRC adamantly opposed further cutoffs, either natural or artificial. Corps attitudes were shaped largely by Charles Ellet, Jr., an influential engineer under contract to the Federal government, who in 1851 warned that river cutoffs were detrimental and actually presented increased dangers of flooding. Ellet's beliefs were echoed 10 years later by Captain Andrew A. Humphreys and Lieutenant Henry B. Abbot in their report for the Corps, *Physics of the Mississippi River*. Humphreys and Abbot specified, mistakenly, that although cutoffs lowered water stages upriver, they increased river stages below them by half as much. Later events appeared to support their argument. Three natural cutoffs above Memphis and one at Vicksburg in the 1870s and another at Waterproof, Louisiana, in 1884 produced drastic changes in the Mississippi River's alignment, wiped large tracts of agricultural land literally off the map, and interfered seriously with navigation. Corps and MRC activities thereafter concentrated on preventing rather than encouraging cutoffs.

As always, disasters stimulated reanalysis. Following the great Mississippi River flood of 1897, longtime river student James B. Miles recommended cutoff construction to Congress. He uncannily predicted the exact number of cutoffs and exact mileage reduction in the length of the river as that of the plan adopted and executed 40 years later. Miles and others argued that shortening and straightening the river would lower its bed, lower the level of flood stages, and hasten the flow of floodwaters to the Gulf. In the aftermath

Greenville Bends exemplified the meandering regime of the Mississippi River

of the 1927 superflood, William E. Elam, Chief Engineer of the Mississippi Levee District, presented a paper to the ASCE in which he attempted to show the benefits of cutting off the river's Greenville Bends, a notorious labyrinth of loops near Greenville, MS.[23] Elam and other engineers favoring cutoffs had no clear plans of how to execute and control such operations in a river as large as the Mississippi.

Corps policy even after the disaster of 1927 remained staunchly opposed to cutoffs. The "Jadwin Plan," which Congress had accepted in 1928 as the Corps' master design for flood control on the Lower Mississippi, pointedly did not include cutoffs, as Jadwin was a vocal opponent. Yet only four years later, the Corps was committed to a massive cutoff program with WES playing a major role.

The Corps Opts for Cutoffs

Cutoff advocates received a boost from a timely natural occurrence. In the fall of 1929, shortly before Vogel relocated from Memphis, about 40 miles downriver from Vicksburg the Mississippi River completed a natural cutoff. Called the Yucatan Cutoff, it was especially unusual because it came at low water. Jackson and Vogel visited the site in December. The new channel, which took another two flood seasons to capture the majority of the main stem's flow, was also atypical in that it was not across the narrowest part of the neck of the bend, but rather passed through a slightly curving channel nearly two miles in length. Since it did not upset the river either upstream or downstream in a detrimental way, some observers rightly concluded that a narrow channel a mile or two in length and gradually developed — like the Yucatan — was superior as a cutoff route to the typical short, wider cuts across narrow necks of land. Mild curvature of the channel also seemed advantageous in preserving a deep navigation channel. Learning from nature, cutoff advocates then called for "shortening but not straightening" the Mississippi.

Although engineers positively influenced toward cutoffs by the Yucatan event still formed a minority in the engineering community at large, and certainly within the Corps, their numbers included Colonel Harley B. Ferguson, then South Atlantic Division Engineer. By the late 1920s Ferguson had become the Corps' most outspoken proponent of cutoffs, and on 22 November 1930, he submitted a report recommending cutoffs in the 370-mile stretch of the Mississippi between White River and Old River. Instead of adopting the European technique of making dry cutoffs to the full dimensions of a river's channel, then diverting the river into the cut, Ferguson promoted a pilot-cut plan that permitted a more leisurely approach. Integral to Ferguson's thesis was allowing the river to gradually do the major part of excavating a new channel. This would avoid high velocities at the time of diversion and prevent raised flood stages downstream, both invariable results of the European method. Bold in concept and without precedent, Ferguson's ideas soon gained the confidence of Chief of Engineers Brown, who became a staunch patron. Brown later stated that

Colonel Harley B. Ferguson

> *Ferguson was the first and only responsible man who ever brought to the Chief of Engineers the serious proposition to make artificial cutoffs on the Mississippi River. Whatever credit is due for a courageous effort to lower the height of floods on the confined waters of the Mississippi is due to ... Harley B. Ferguson.*[24]

Reflecting his faith in Ferguson and his new-found advocacy of cutoffs, Brown appointed Ferguson to replace Jackson as president of the MRC in July 1932.

Yucatan Cutoff provided a natural clinic for cutoff studies

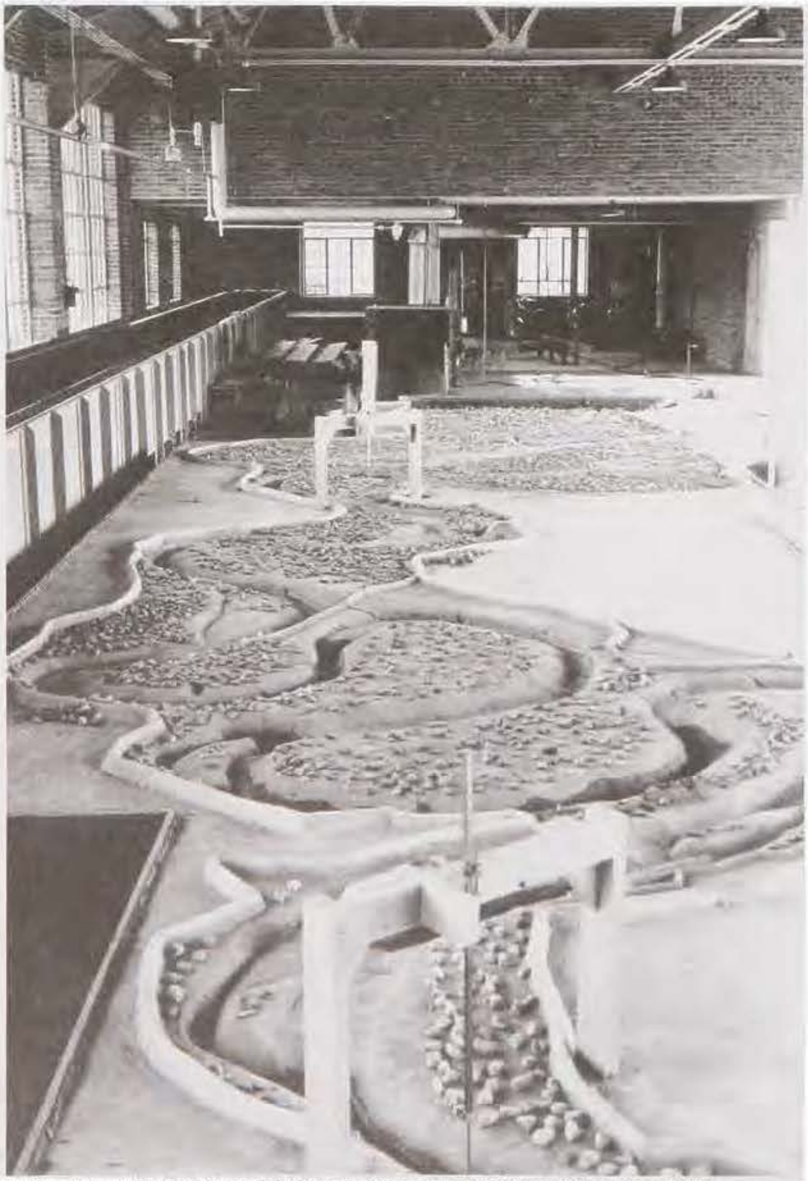
First WES Cutoff Model

Vogel had begun model studies of cutoffs long before the arrival of Ferguson. In November 1930 the Office of the Chief of Engineers had ordered MRC President Jackson to begin an investigation of the effects of cutoffs in the Greenville Bends. On 18 November Jackson instructed the Vicksburg District to initiate a full field study. On the same day he directed Vogel to perform a model study of the effects of cutoffs at each of the four necks in the Greenville Bends.[25]

In December 1930, at the same time that its Ohio River dam models were in use, WES began construction of an indoor model of the Greenville Bends reach. The 80-foot-long structure represented 98 miles of the Mississippi River, stretching from immediately below the mouth of the Arkansas River to four miles below Lake Lee, south of Greenville (River Mile 401 to River Mile 499). Initially built as a movable-bed model with a sand bed and gravel added to simulate rough overbank conditions, the model in its first two series of tests showed "no substantial agreement" with readings taken directly from the river. Consequently, technicians concreted the channel in place and made other adjustments. On the third test series, measurements on the model agreed closely with those observed in nature.

After this verification, over a period of months experiments enabled project engineers to predict stages in the Mississippi River at different points in the Greenville Bends for a variety of cutoff scenarios. Calculation of river stages was complemented by other projections. After exhaustive trials WES personnel found that well-soaked, creosoted sawdust ideally simulated natural detritus movement in the model. This material was used to determine what sedimentary deposits might be formed as a result of cutoffs. Threads placed in the model indicated the direction of currents, and dyes injected into the upstream reaches revealed eddies and other current phenomena.

Test results, published in April and August 1931, pointed to a revolutionary conclusion: cutoffs did not raise river levels below them. All studies, in fact, indicated a general lowering of flow lines above cutoffs — 2.2 feet in the case of Tarpley Neck — and that any rising of flow lines below cutoffs were short term. This further contradicted the theories of Humphreys and Abbot. The model also gave no indication of detrimental effects due to cutoffs, but showed a slight tendency toward improved conditions in some cases.[26]



Indoor Greenville Bends model pioneered use of models for cutoff studies, 1931

Outdoor Greenville Bends model 1932

Outdoor Cutoff Model

In the spring of 1932 WES constructed a larger, outdoor model for cutoff studies. Taking advantage of the existing Yazoo Basin model that included the adjoining stretch of the Mississippi River, project engineers extended the Mississippi River part of the model to simulate another 155 miles downstream to Old River. The entire complex represented about 280 river miles and covered 17,000 square feet, including the Yazoo Basin. The upper portion of the outdoor model overlapped 16 miles of the lower portion of the indoor Greenville Bends model.

Outdoor model tests concentrated on the effects of cutoffs at seven locations, ranging from just downstream of the Greenville Bends at Sarah Island to Esperance Point below Natchez, MS. Conclusions, derived from both the indoor and outdoor models and published in April 1932, were mixed. The WES report, for instance, indicated that a cutoff at Diamond Point, about 15 miles downstream from Vicksburg, would have a number of good effects and no bad ones. Cutoffs near Natchez were seen as having "dubious" value, and a cutoff considered at Ashbrook Neck in the Greenville Bends, according to the model study, should be "studiously avoided."[27]

Ferguson and the Cutoff Program

Ferguson succeeded Jackson as MRC president in June 1932. In the administrative transition, he brought cutoff proponent Gerard H. Matthes from the Corps' Norfolk (Virginia) District to take over as the MRC's Chief Engineer. Both Ferguson and Matthes took an immediate interest in Diamond Point as the potential site of a manmade cutoff. According to Vogel, Jackson had already begun field work for a cutoff at Diamond Point before his


Observers at Diamond Point Cutoff, 1933

departure from the MRC, but this was vehemently denied later by Matthes.[28] In either case, Ferguson ordered cutoff work at Diamond Point to proceed posthaste.

As the first manmade cutoff in nearly a century, the Diamond Point project served as the initial test for both Ferguson's master plan and the WES model study. In September 1932, two hydraulic dredges began excavating channels on opposite sides of the bend's neck, working toward each other, and by January 1933 only a 50-foot-wide plug separated the two. Amid substantial fanfare, Ferguson on 8 January 1933 departed from Vicksburg on the steamer *Control*, accompanied by a quarter boat and party that included Vogel. Standing on the banks of the cut, the group watched as four dynamite blasts removed the final barrier. Because the river level on the upstream side was almost 5 feet higher than the downstream, water rushed through a shallow trench, quickly causing the banks to cave in and clearing a 60-foot-wide channel. Thereafter, as intended, the channel expanded gradually without disrupting the river's normal levels, capturing only 10 percent of the flow in the next two weeks. The new channel did not capture the majority of flow until the spring of 1937, and by the end of that year had become the main stem.[29]


Greenville Bends aerial view after cutoffs

Interpreting the Diamond Cutoff as a total success and vindication, Ferguson proceeded vigorously in implementing the remainder of his cutoff program. By 1939, when Ferguson left the MRC, 12 manmade cutoffs had been completed that, when combined with the Yucatan Cutoff, shortened the Mississippi by about 115 miles between Memphis and Baton Rouge.[30] Three later cutoffs increased the total shortening to 170 miles by 1942.

Throughout the Ferguson era WES continued to perform cutoff model studies, but their influence was, and is, debatable. Matthes in 1948 stated that the early WES reports were important in showing that river stages did not rise below cutoffs, but that, with the exception of the cutoffs proposed at Greenville Bends, WES findings were

"far from encouraging," were "adverse to undertaking most of the cutoffs proposed," and were "of no help to General Ferguson." The fixed-bed models, Matthes continued, were of solid concrete and were incapable of simulating bank and bed erosion, factors basic to Ferguson's plan for channel rectification and bank stabilization that would accompany cutoffs. Cutoff model studies improved beginning in the summer of 1932, according to Matthes, when Ferguson ordered that experiments be conducted with erodible beds. Even then, data indicated that cutoffs at several projected locations would be ineffective.[31]

Convinced as to the validity of his theories, Ferguson was not likely to be strongly influenced by laboratory data, discouraging or not. Paul W. Thompson, Vogel's Assistant Engineer in 1932 and 1933 and third WES Director from July 1937 to September 1939, described Ferguson as "impatient of experimental results that failed to fit his own instinctive conclusions," but also as a man whose "instinctive conclusions were...often and uncannily right." Thompson believed that, in spite of denials by Matthes, the WES studies still "played an important part — more important than [Ferguson] ever admitted or perhaps ever realized."[32] In any case, the cutoff program went forward unabated.

New Madrid Floodway

Part of the Corps' general plan for flood control on the Lower Mississippi River involved the creation of floodways: areas into which floodwaters could be diverted until water levels receded on the main stem, or could be routed to the Gulf of Mexico through alternate paths. The Birds Point-New Madrid Floodway was one of three constructed beginning in 1929. Located in Missouri and starting just below the confluence of the Mississippi and Ohio Rivers at Cairo, IL, it covered about 206 square miles. Engineers created it by lowering existing levees at selected points near the Mississippi by 5 feet, then building new levees about 5 miles farther west, away from the river. Conceptually, during very high flood stages, floodwaters would crevasse the shortened levees, diverting a portion of the river's flow through the leveed floodway and lowering flood stages at Cairo.

Lacking precise data, the MRC in 1932 ordered WES to perform a model study to determine the effects of operating the floodway on the lands lying within it and to predict the draw-down on the Mississippi River with the floodway in use. With more than 100 miles of river to simulate, WES built an 80-foot-long outdoor concrete model of the river channel, the overbank between levees, backwater areas, and the floodway. Designers took special care to correctly place drainage ditches, levee borrow pits, and other details that would affect water levels, and raised miniature levees with soil taken from actual on-site levee borings. After comparing water levels and flows in the model with gage readings from the Mississippi, project engineers made the usual necessary adjustments (such as adding gravel to overbank areas to simulate roughness) until model and prototype readings agreed. Gage readings from the six highest floods in the vicinity since 1882 provided data for water levels and flows in the experiments. Model tests indicated that the new levees were high enough to contain any projected flood, that levels in the Mississippi would be lowered substantially during use of the floodway, and that the lands of the floodway would suffer almost no permanent damage from inundation.[33]

Other Model Investigations

While most early activities at WES were centered around flood control projects on the Mississippi River and its tributaries, a number of experiments reflected a broader range of river engineering concerns. These included erosion control in floodways and along riverbanks, channel improvements for navigational purposes, and improved design of appurtenances for hydraulic structures. In January 1931 the MRC directed Vogel to determine if extensive erosion could be expected at dredged borrow pits in the Bonnet Carré Floodway, just north of New Orleans. Railroad companies were concerned that erosion at the borrow pits would undermine trestles and threaten elevated railway structures. WES designed a small outdoor model — only 30 feet long by 12 feet wide — that represented the floodway from the Bonnet Carré spillway almost to Lake Pontchartrain. Again demonstrating the ability to devise models for unique situations, personnel surfaced

the cleared land areas in the floodway with cement mortar, but left ditches and borrow pits hollowed out from erodible natural soil. Spanish moss yielded a realistic covering for heavily wooded swamp areas, and other finishing touches included placing miniature railroads, complete with scale-model trestles, across the model. Results from experiments indicated that, although erosion could be expected in some places, it posed no threat to the trestles.[34]

Bonnet Carré Floodway model

Early in 1931, a related study attempted to quantify the erosive actions and general destructive effects of floodwaters on low railroad embankments. This led to construction of a full-size railroad embankment, replete with crossties and track, in the 20-foot-wide canal leading from the spillway of the WES lake. In a pilot test, flood-level waters released from the lake cascaded over the embankment for over two hours while WES engineers took gage readings, motion pictures, and still photographs. Eventually the embankment withstood over 200 hours of flood-level inundation. To complement the outdoor tests, WES personnel designed and constructed scale-model embankments in an indoor flume, then duplicated outdoor tests with different grades of rock and riprap reinforcement. Both test series provided guidelines both for predicting flood damages to railroad embankments and for more efficient construction or remediation.[35]

Full-sized railroad embankment

Observers at railroad embankment test, 1931; note WES building in background

of expertise to include the engineering challenges of coastal inlets, harbors, and tidal estuaries. These prototypes presented a highly complex set of interrelated phenomena such as astral tides, littoral currents, wave action, wind action, salt water intrusion, and other factors not encountered in river engineering.

WES work in harbor engineering began in December 1932 when the Gulf of Mexico Division requested a model study to determine the more efficient of two proposed routes for a ship channel between St. Andrews Bay, Florida (the location of Panama City), and the Gulf of Mexico. In a demonstration of speed

Other early experiments evaluated existing or proposed hydraulic structures. Models of nine locations on the Mississippi River dealt with proper placement and structure of dikes. For example, at Point Pleasant, Missouri, about 80 miles downriver from Cairo, local authorities had called for the removal of an existing dike system and its replacement with another. WES model experiments evaluated several plans, including leaving the existing dike system intact, removal of all dikes, and replacing or supplementing the existing system with alternative systems. Because the existing system functioned as well as any of the proposed alternates in the model, engineers took no action. This prevented unnecessary construction and avoided major costs.[36] A similar study performed for the Jacksonville District showed the need for modification of spillway designs on the St. Lucie Canal. Model experiments covered six weeks and cost only $500, but resulted in a net savings of $25,000 in concrete use alone.[37]

First WES Tidal Model

Prior to 1933, the degree of diversity reflected by experimental activities at WES was moderate. In its first two years the Station concentrated almost exclusively on the engineering problems of inland waterways — flood control and river regulation/improvement for navigational purposes. This began to change as WES broadened its areas

St. Andrews Bay Panama City, FL; the first WES harbor model

and skill developed over its two years of operation, WES designed, built, and verified a harbor model in only two weeks. The indoor structure replicated about 100 square miles of St. Andrews Bay and the surrounding area. Made of concrete, the model exactly reproduced the topography of the mainland and the bed of the Gulf of Mexico, but the bed of the bay in the model was concreted lower than the bed of the prototype. Project designers then covered the bed of the lowered model bay with a 2-inch layer of fine sand. This, they hoped, would provide the model with both fixed-bed and movable-bed characteristics where needed.[38]

Borrowing largely from European methods, WES operators attempted to reproduce the intricate hydraulic functions of the bay in several ways. Water flowing into the model from the proper direction simulated littoral currents, while raising or lowering the tailgate of the model reproduced tides. In a simple but effective procedure, workers used a gate extending the length of the Gulf of Mexico, inclined away from the model and hinged at the bottom, to simulate waves. A trained worker raised the gate with a hand crank, then allowed it to fall back to its position of rest. This generated a wave parallel to the shoreline. Through experiment and practice, engineers standardized the frequency and intensity of the waves until satisfactory results were obtained. Finally, 10 electric fans mounted on the Gulf of Mexico side of the model simulated winds from various angles to the shore and the surface of the water. WES experiments led the Gulf of Mexico Division to selection of a plan of improvement, but later developments in the prototype were highly disappointing (discussed in Chapter 3).[39] The Station's first attempt at harbor modeling was not a success.

Theoretical Research

Although WES was created as a practical institution intended to help engineers with problems in the field, part of its work turned to more theoretical considerations. The physics of water flow at river bends, for instance, had perplexed engineers for centuries. In 1876 James Thompson had published an interpretation in the *Proceedings* of the Royal Society of London that gained general acceptance into the 20th century. Based on the

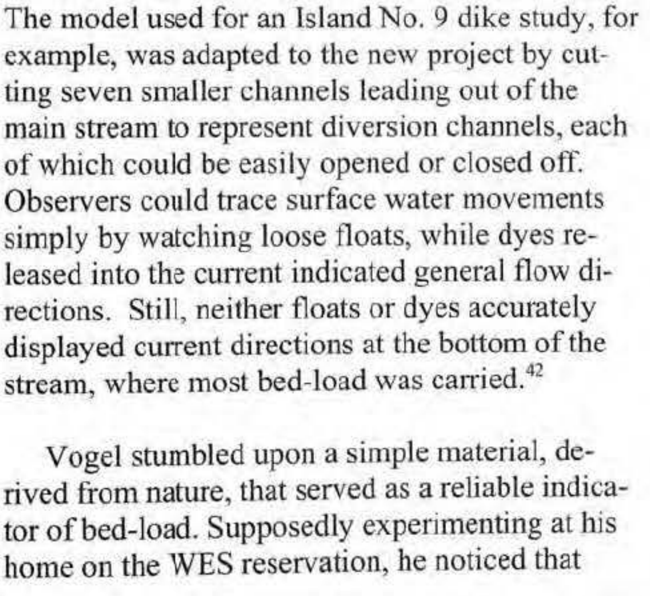
Movement of bed materials model

concept that water formed a helix or spiral as it flowed around a bend, Thompson's "heliocoidal theory" explained how materials from the concave (outer) bend of a river were transported by currents to the convex (inner) bend to create deposits or bars.[40]

In October 1932 Vogel, at MRC direction, initiated a series of experiments to study the movement of bed-load materials around bends. Particular attention was to be paid to the possibility of removing materials from the bed of a main stream by means of diversion channels. Once removed from the main channel, materials could be deposited as fill in low areas or passed along floodways, improving navigation and possibly helping reclaim swamp lands.[41]

Since WES already had outdoor models of several Mississippi River bends for its cutoff and channel improvement investigations, Vogel used them rather than engaging in new construction. The model used for an Island No. 9 dike study, for example, was adapted to the new project by cutting seven smaller channels leading out of the main stream to represent diversion channels, each of which could be easily opened or closed off. Observers could trace surface water movements simply by watching loose floats, while dyes released into the current indicated general flow directions. Still, neither floats or dyes accurately displayed current directions at the bottom of the stream, where most bed-load was carried.[42]

Vogel stumbled upon a simple material, derived from nature, that served as a reliable indicator of bed-load. Supposedly experimenting at his home on the WES reservation, he noticed that ordinary oat grains sank to the bottom of moving water with the heavier head resting on the bottom and the lighter chaff end pointing in the direction of flow, somewhat like a wind vane. Model operators further observed that oat grains drifted down channels to the concave side of the bends, then crossed to the convex side. The movement was not continuous or uniform, but was "jumpy, rolling, and sporadic." Of primary importance, grains invariably tended to move from regions of high velocity toward regions of low velocity, such as in the convex side of a river bend. Vogel deduced that bed materials were not swept across riverbeds by currents but were drawn to regions of low velocity by other forces, and that the heliocoidal theory of bed movements did not apply to broad rivers such as the Mississippi. As a practical result, model tests indicated that substantial amounts of bed-load material could be diverted by natural processes from main channels into secondary channels with lower velocities.[43]



Oat grains provided a convenient material to simulate bed materials

In a related study, Vogel supervised experiments to calculate the amount of bed-load diverted into a side channel of a straight flume rather than a river bend model. Noting that prior studies in Germany, performed primarily at Karlsruhe and sponsored by Rehbock, had limited applications, Vogel designed a larger and more practical apparatus than anything used in Europe. The WES flume was over 30 feet long with a 2-foot-wide cemented main channel. About 11 feet from the head of the main channel a 1-foot-wide side channel angled 30 degrees to the right. The proportional widths and angle of diversion represented the most commonly found conditions in nature, especially in the Mississippi Valley. Although similar devices were generically known as forked flumes, the Station christened its creation the more distinctive bifurcated flume. Tests conducted by Lieutenant Kenneth D. Nichols and C.D. Curran, under Vogel's supervision, involved introducing bed-load materials into the flume, then observing and carefully measuring the amounts carried by and deposited in the main channel and the diversion channel. Improving on German methods, the WES experiments used a variety of bed-load materials, usually sands, that could differ substantially in behavior, and also allowed exact measurement of materials carried completely through the model. As in the outdoor river bend model tests, results indicated that bed-load materials tended to

WES bifurcated flume looking upstream

WES bifurcated flume looking downstream

move toward lower water velocities and that disproportionate percentages of bed-load materials moved to the smaller channel.[44]

A third study related to bed load movement involved a lengthy series of indoor flume tests to determine the force of flowing water required to move the bed materials of the Lower Mississippi River. In 1932 Thompson designed a flume used throughout the testing sequence. Tiffany and then C.E. Bentzel succeeded him as project engineer. Because the study concentrated on the bed materials of the Lower Mississippi, the MRC acquired about 750 large samples taken directly from the river bottom. Workers molded the materials in the flume to simulate the river bed, adjusted the flume to a desired slope, then slowly flooded it from the lower end to avoid disturbing the bed. For the first time, tests provided a mass of data concerning specific bed materials, their location in the Lower Mississippi, the force of flow required to move them, their settlement tendencies, and other factors.[45]

Bifurcated flume tests also led to improved instrumentation. When work necessitated accurate determinations of water velocity and discharge distributions in the channels, standard velocity measuring devices proved too slow or imprecise. Bentzel then devised a velocity tube based on

C. E. Bentzel with tube in action

principles he had conceived while designing a flow meter for the gasoline line of his automobile. He secured the first WES-related patent on the instrument, with the right of manufacture retained by the U.S. Government.[46]

Expanded Mission: Soil Mechanics

While the Station emerged as the Corps' premier hydraulics research center, its mission expanded to incorporate other engineering fields. By the early 1930s, several American institutions, notably MIT and Harvard, began to offer courses and perform research in the new field of soil mechanics, later known as geotechnical engineering. Since many areas of hydraulics engineering such as sedimentation analysis, levee design, and underseepage of earthen structures, involved soils-related studies, WES incorporated soils testing into its activities at an early date. In 1931, just as the first WES hydraulics models were built, a small group of technicians began conducting mechanical analyses of bedload samples and sediment from the Mississippi River on a part-time basis. Housed in the west wing of the main WES building, this informally named Soils Section had by the late-1930s expanded its activities far beyond the support of hydraulics engineering at WES.

Spencer J. Buchanan

Soil mechanics at the Station received an enormous boost in 1933 when Vogel hired Spencer J. Buchanan, a Texas native and recent MIT graduate, to head soils-related work. Buchanan subsequently built the soils engineering program at WES into the most important in the Corps of Engineers before his departure in 1940. In 1939 WES established a Soil Mechanics Division on an administrative par with the Hydraulics Division. This set a precedent followed later in a number of cases: units originating in the Hydraulics Division to support the Station's hydraulics mission split away to form separate entities. As in the case of the Hydraulics Division, these became national and even world leaders in their respective fields.[47]

Hydraulic Modeling Ascendant

Vogel's tenure as WES Director ended in August 1934 upon his transfer to Command General Staff School. Less than five years had passed since his arrival in Vicksburg at the end of 1929, and less than four since the first WES experiments began in December 1930. Yet he had supervised a remarkable, and largely unanticipated, growth and transition. Carved from an overgrown creek bottom at the outskirts of a sleepy Southern river town, by Vogel's departure the Station had become the primary hydraulics research institution not only for the Corps of Engineers, but arguably for the entire nation. The increasing volume and diversity of work reflected the Station's prominence, rising from 13 projects in progress in Fiscal Year 1931 to 54 in Fiscal Year 1934. Vogel, in a 1934 article for *The Military Engineer*, boasted that WES models "in both number and size surpass those of any similar institution in the world." These served not only the needs of the MRC and Lower Mississippi Valley Division, but were used to perform experiments for districts representing every Corps division in the United States except two.[48]

The accomplishments of WES in the Vogel years are even more impressive upon consideration of the limiting factors present at its establishment:

- official opposition of the Corps to the establishment of a hydraulics laboratory until 1929,
- slow acceptance of hydraulic modeling by Corps leaders even after the establishment of WES,
- strong support for a national hydraulic laboratory not under Corps control, and
- European primacy in hydraulics engineering prior to the 1930s.

By 1934 the situation had changed fundamentally in regard to all, and Vogel was largely responsible. With modest financial resources and in a time of national crisis, he had molded WES into a viable institution that was beginning to place the Corps at the leading edge of hydraulic modeling research. Numerous publications in the foremost professional journals of the time indicated the acceptance, both within and outside the Corps, of hydraulic modeling and of the Station's prominent role. Vogel, for example, defined the state of the art in river hydraulics in an article for the ASCE *Proceedings* of November 1933, an effort upgraded to the ASCE *Transactions* of 1935, with commentary.[49]

Perhaps the most striking statement in support of the success of Vogel, of WES, and of the American engineering community, was derived from a tour Vogel made of German laboratories in the summer of 1934, just prior to his leaving WES. This was his first return to Germany since receiving a Ph.D. from the Berlin *Technische Hochschule* in 1929. Whereas Germany had been the unchallenged leader in hydraulic modeling at the time of Vogel's graduate studies, he now sensed a remarkable change. In comparing German and American advances in the interim, he noted that since 1929 the Germans had made "considerable progress...but the advancement has been not nearly as rapid, or upon as broad a front, as in the United States." International leadership in hydraulics engineering was shifting across the Atlantic. Still, the Station had only begun to realize its potential.

Notes

1.Herbert D. Vogel, interview by Sue Ellen Hoy; and Vogel, "Origin of the Waterways Experiment Station."

2.Ibid.; and Frederick R. Brown, interview by author, Vicksburg, 3 June 1994.

3.Vogel, interview by Sue Ellen Hoy; Vogel, interview by Michael C. Robinson; Vogel, "Origin of Waterways Experiment Station."

4.John J. Franco, interview by author, Vicksburg, 18 July 1996.

5.Herbert D. Vogel, interview by Sue Ellen Hoy.

6.Frederick R. Brown, letter to author, 8 June 1994.

7.See Lieutenant Francis H. Falkner, *Final Report to the President, Mississippi River Commission on Activities of the U.S. Waterways Experiment Station from July 1, 1934 to July 1, 1937* (Vicksburg: WES, 1937), 52, for a complete breakdown of the number and classification of employees from 1931 to 1937.

8.See Lieutenant Francis H. Falkner, *Final Report to the President, Mississippi River Commission on Activities of the U.S. Waterways Experiment Station from July 1, 1934 to July 1, 1937* (Vicksburg: WES, 1937), 52, for a complete breakdown of the number and classification of employees from 1931 to 1937.

9.Tiffany, *History of WES*, V-3-4.

10.Ibid.; and Falkner, *Final Report*, 60-61.

11."New Plans for the Mississippi," *Engineering News-Record*.

12.Rouse, 91. For a detailed account, see Martin E. Nelson, "Laboratory Tests on Hydraulic Models of the Hastings Dam," *University of Iowa Studies in Engineering, Bulletin 2* (Iowa City, Iowa: Iowa University, 1932), also published as *St. Paul District Hydraulic Laboratory Report No. 1* (St. Paul: n.p., 1932).

13.*Hydraulic Studies of Proposed Dam No. 37, Ohio River. Paper D of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1931).

14.Ibid.

15.A full discussion of the Illinois River backwater project, with data, is included in *Experiment to Determine the Limit of Backwater Influence in the Illinois River. Paper Y of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1931). Also see Vogel, "Origins of the Waterways Experiment Station"; and Tiffany, *History of WES*, I-5.

16.*Paper Y of the U.S. Waterways Experiment Station.* Bardsley's role in the Illinois River model project is puzzling. Vogel stated in "Origins of the Waterways Experiment Station" in 1961 that Bardsley spent one summer at the Station. Vogel also stated in a 1976 interview that Bardsley had a "one-summer job" at WES. The model, however, was constructed in mid-winter. More puzzling, Vogel wrote for *The Military Engineer* that "Templates were cut from sheet metal and fitted to the ground which Bardsley *carved out with a grapefruit knife* [emphasis added] to form a miniature river channel." This cryptic description has become an integral part of the Station's lore, repeated in many publications and photo captions of the model. The WES brochure for visitors, for example, notes of the Station's modest beginnings that "our first model was dug with a grapefruit knife." Because the model was almost 600 feet long and appears to be about two feet deep, this seems highly unlikely. Also, photographs clearly show a workman using a shovel.

17.Ibid.

18.Ibid.

19.Cotton in his *History of WES* states that "the first test had to be satisfactory, for the dirt could not be compacted and recarved." The model actually survived several test runs before experiments were completed.

20.*Experiment to Determine the Effects of the Several Proposed Levee Extensions South of Eagle Lake, Mississippi. Paper A of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1932).

21.Ibid.

22.The area was one of the most hydraulically active in the world, eventually requiring massive control structures.

23.See W.E. Elam, "Discussion: Elam on Mississippi River Flood Control," *Transactions of the American Society of Civil Engineers* 93 (1929): 937.

24.Lytle Brown, "Discussion: Brown on Cutoffs," *Transactions of the American Society of Civil Engineers* 113 (1948): 22.

25.*Experiment to Determine the Effects of Proposed Dredged Cutoffs in the Mississippi River. WES Paper I* (St. Louis: MRC, 1932).

26.Ibid.

27.Ibid.

28.See Herbert D. Vogel, "Discussion: Vogel on Cutoffs," *Transactions of the American Society of Civil Engineers* 113 (1948): 19; and Gerard H. Matthes, "Discussion: Matthes on Cutoffs," ibid., 113 (1948): 31. Vogel strongly championed Jackson's role in sponsoring cutoffs before the arrival of Ferguson, stating that "General Jackson pioneered the way, overcoming prejudices and fears of long standing." Matthes conversely noted that "Vogel evidently labored under a misapprehension when he stated...that General Jackson pioneered the way." Further, Matthes claimed that Ferguson made the decision to locate a cutoff across Diamond Point on 17 June 1932, two days after becoming MRC President, and that nothing had been done prior to that date. See Brigadier General H.B. Ferguson, *History of the Improvement of the Lower Mississippi River for Flood Control and Navigation, 1932-1939* (Vicksburg: Mississippi River Commission, 1940), 49-50.

29.Ibid.

30.See Harley B. Ferguson, "Construction of Mississippi River Cut-Offs," *Civil Engineering* 8 (1938): 725-29; and Harley B. Ferguson, "Effects of Mississippi River Cut-Offs," *Civil Engineering* 8 (1938): 826-29.

31.Matthes, "Discussion," 31-2.

32.See Paul W. Thompson, "Comments of Former Directors," in Tiffany, *History of WES*, IV-1-4.

33.*Model Study of Effects of Operating Birds Point-New Madrid Floodway. Paper C of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1932).

34."Report of Experiment to Determine the Erosion at Upper Ends of the Dredge Borrow Pits in the Bonnet Carré Floodway," WES *Technical Memorandum 0-2* (Vicksburg: WES, 1931). This was the first WES report other than the "HYDRAULICS"series to be entitled *Technical Memorandum* followed by a serial number. In 1956 WES administrators changed the nomenclature to *Technical Report*. Beginning in 1952 other publications, often of more general interest, were titled *Miscellaneous Paper*, again followed by a serial number. All normally include valuable information on sponsoring agencies, project dates, personnel involved, and technical data. Unfortunately, early publications do not list authors in their titles. In some cases authorship of older works can be derived from introductory statements. WES publications did not routinely list authors until the mid-1960s. Citations in this work included authorship whenever ascertainable.

35.*Experiment to Determine the Erosive Effects of Floodwaters on Railroad Embankments. Paper R of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1931); and "New Plans for the Mississippi: Special River Problems Studied by Models," *Engineering News-Record* 110 (1933): 79.

36.*Model Studies of Dike Location. Paper 11 of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1933); and *Model Studies for Channel Stabilization, Mississippi River.*

Paper 15 of the U.S. Waterways Experiment Station (St. Louis: Mississippi River Commission, 1933).

37.*Annual Report of the Chief of Engineers, U.S. Army, 1932. Report of the President of the Mississippi River Commission* (Washington, D.C.: U.S. Government Printing Office, 1932), 1990; and *Model Studies of Spillways for St. Lucie Canal, Martin County, Florida. Paper 14 of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1933).

38."Report on Progress to Date: Experiment on Ship Channel Relocation, St. Andrews Bay, Florida," WES *Technical Memorandum No. 13-2* (Vicksburg: WES, 1933); and "St. Andrews Bay, Florida, Experiment on Ship Channel Relocation, Supplementary Report on Contraction Works," WES *Technical Memorandum No. 13-3* (Vicksburg: WES, 1933).

39.Ibid.

40."Model Study of the Movement of Bed Material Around Bends and Through Diversion Channels," WES *Technical Memorandum No. 3-1* (Vicksburg: WES, 1933); and Herbert D. Vogel and Paul W. Thompson, "Flow in River Bends," *Civil Engineering* 3 (1933): 266-68.

41.Ibid.

42.Ibid.

43.Ibid.

44."Study of the Bed Load Movement in a Forked Flume," WES *Technical Memorandum No. 4-4* (Vicksburg: WES, 1933); and Herbert D. Vogel, "Movement of Bed Load in a Forked Flume," *Civil Engineering* 4 (1934): 73-77.

45.*Studies of River Bed Materials and Their Movement, with Special Reference to the Lower Mississippi River. Paper 17 of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1935).

46.Francis H. Falkner, "The Bentzel Velocity Tube," typewritten manuscript, WES Archives, provides a full discussion.

47. Fatherree, *The Earth Inherited. WES Laboratory History Series, Volume II: History of the Geotechnical Laboratory*.

48.Herbert D. Vogel, "Organization and Operation of the Waterways Experiment Station," *The Military Engineer* 36 (1934): 121-22. Complete project lists are included in the *Annual Report of the Chief of Engineers. Report of the President of the Mississippi River Commission* for each fiscal year.

49.Vogel, "Practical River Hydraulics."

3 Coming of Age, 1934-1941

Falkner as Director

Lieutenant Francis H. Falkner

In August 1934 Lieutenant Francis H. Falkner, who had interned at the Station in 1933, returned to succeed Vogel as second WES Director.[1] On assuming the office, he inherited a situation far different from that of his predecessor. Whereas Vogel had first met with great skepticism as to the worth of hydraulic modeling, this reticence had dissipated by the end of his WES tenure. Falkner, in fact, found the use of models by the Corps of Engineers to be almost universal, with field engineers "the most ardent enthusiasts about hydraulic model work." This remarkable swing of the pendulum, Falkner feared, presented a dangerous problem in that engineers had developed "unwarranted expectations" from model tests before results in the field were actually verified. Part of this, he felt, was due to "an overly optimistic picture" presented in early WES reports.[2]

In its new-found enthusiasm for models, Falkner also felt that the Corps had lost its focus. Popular conceptions of hydraulic models, especially as portrayed in periodicals, had led many field engineers to believe that anyone could design and operate a model. Consequently, many of the Corps' district or division engineers, rather than referring work to WES, built their own models on location or farmed out work to nearby universities. The Corps had also established five permanent hydraulic laboratories in addition to WES to engage in long-term studies, and eight temporary laboratories, each concentrating on a specific problem. According to Falkner, this multitude of facilities, uncoordinated by any centralized authority, duplicated efforts and often suffered from inexperience or outright faulty methods.[3]

Corps of Engineers Permanent Hydraulic Laboratories, 1936[4]

Name of Laboratory	Location	Date Founded	Capability	Projects Investigated
Waterways Experiment Station	Vicksburg, MS	1929	30 Projects	181
U.S. Engineer Sub-Office, St. Paul District	Iowa City, IA	1929	12 Projects	46
Caisson Plant, Milwaukee District	Milwaukee Harbor	1931	1 Project	4
U.S. Beach Erosion Board Wave Tank	Fort Belvoir, VA	1932	1 Project	9
Linnton Hydraulic Laboratory, Portland District	Portland, OR	1934	3 Projects	5
U.S. Tidal Model Laboratory, North Pacific Division	Berkeley, CA	1934	2 Projects	9

Despite the plethora of Corps laboratories and universities engaged in hydraulic modeling, WES had emerged as a clear leader in certain areas. Of Corps-sponsored investigations related to flood control, WES had performed 38 studies by 1936, compared to none for other government laboratories or universities. In studies of open river regulation for navigation, WES had completed 44 projects for the Corps, a university laboratory one, and other government labs none. Work concerning river canalization, however, fell mostly to other institutions. The Station conducted only four studies in that area compared to 44 for other government labs and four by universities. WES also trailed in research on hydraulic features of fixed dams and on coastal harbors and beaches.[5] By the late 1930s, as the Corps began to centralize its research efforts, WES began to surpass other institutions in most of those fields as well.

Organizational Evolution

For more than a year after assuming command, Falkner retained the three-section administrative structure established by Vogel in September 1933:

- Experiment
- Research and Publications, and
- Operations.

Then in a major overhaul in November 1935, Falkner abolished both the Experiment and the Research and Publications sections and set up a project engineer system. In place of the four groups within the Experiment Section — fixed-bed model, movable-bed model, tidal model, and soils — he selected a group of the more able engineers and assigned a single project to each. Designated Project Engineers, they were responsible directly to the Director or Assistant Director. Falkner then named Tiffany and Eugene P. Fortson as his Technical Assistants to advise both the Director and the Project Engineers. All engineers not selected as Project Engineers fell into a pool of assistants from which the Project Engineers requisitioned help according to the needs of their studies, often on a daily basis.[6]

Eugene P. Fortson, 1933

Active Projects, March 1937
Project Engineer System

Project	Project Engineer
Maracaibo Bar	R. B. Cochrane
Pipe Line Mixers	G. W. Howard
East River	J. S. Gentilich
Lock & Dam No. 6	E. L. Eustis
Pryor's Island	G. B. Fenwick
Mare Island Strait	A. P. Gilden
Chain of Rocks	S. C. Guess
Dogtooth Bend	J. J. Franco
Helena-Donaldsonville	V. G. Kaufman
Grand Tower	M. J. Ord
Swiftsure Towhead	E. H. Woodman
Sardis Dam Spillway	F. D. Cochrane
Sardis Dam Outlet	F. R. Brown
Manchester Island	R. W. Mueller

In the meantime, Falkner attempted to provide more long-term continuity on an administrative level. Recognizing that protracted programs of experimentation could lose focus due to the relatively short tenure of the Station's military directors, he thought a strong permanent civilian staff was necessary.[7] In the spring of 1935 he contacted Lorenz G. Straub, a Professor of Hydraulics at the University of Minnesota, inquiring as to the possibility of Straub's taking permanent direction of the Station's technical programs. A Missouri native, Straub had earned a Ph.D. from the University of Illinois in 1927 before studying at the *Technische Hochschules* of Karlsruhe and Berlin as one of the first group of ASCE Freeman Scholars. Among other accomplishments, Straub

had translated several German works on hydraulics into English, including Otto Franzius' *Der Verkehrswasserbau* (*Waterway Engineering*).

In April 1935, Straub visited WES. There Falkner offered him a position as "permanent head of our technical organization," a proposition wholeheartedly supported by MRC President Ferguson.[8] A period of jockeying followed during which the University of Minnesota granted Straub a full professorship with substantially increased benefits. Still, Straub requested a year's leave of absence from the university to work at WES before making a final decision. When the university refused this request, Straub chose to remain in Minnesota.[9] Falkner does not appear to have actively sought another candidate. The Station did not have a permanent technical director until Tiffany assumed the position in 1940.

Attempts at Field Verification

From 1934 through 1937 Falkner supervised attempts to develop more rational modeling theories and techniques with verification in the field. As the Station, in a sense, caught its breath and retrenched, its engineers performed fewer studies of specific problems and slowed the publication of technical reports. The number of civilian employees dropped precipitously from a high of 401 at the end of fiscal 1935 to 217 the following year, while the number of projects in progress simultaneously declined from 45 to 34.[10] After the remarkable growth of the previous four years, efforts now concentrated more on substantiating model accuracy and reliability.

Falkner sought to determine if predictions derived from previous WES model tests could be confirmed as accurate. He tried to accomplish this in two ways. First, a he initiated a broad survey that attempted to compare where possible, model predictions with actual performance in prototypes; second, he had WES personnel repeat identical tests in existing models, especially movable-bed types, to ascertain if results were consistent.

In August 1934, in his first month as WES Director, Falkner sent a letter to each of the 20 American hydraulic laboratories and 30 foreign institutions. Specifically, Falkner requested information on hydraulic model predictions that had been substantiated by results obtained in the field. Only 28 laboratories replied, 16 of which were foreign, with responses reflecting an alarming paucity of reliable information. Czechoslovakia, Hungary, Russia, Austria, and Japan offered nothing, while of the four German laboratories that responded, only one acknowledged having ever verified a model study in the field. Data from two institutions in Italy, one each in Holland, Sweden, and Great Britain, and three in the United States provided limited claims of field verifications. Of 17 total cases, only four involved models of open channels, with the remainder referring to weirs, closed conduits, and syphons. Falkner considered the survey a total failure.[11]

Movable-Bed Model Discrepancies

While the Station awaited responses to its questionnaire, its engineers ran a lengthy succession of tests on existing movable-bed models. Most of the Station's experiments in progress at the time were using movable-bed models, and fixed-bed models were much less complex, or controversial. A first-phase series concentrated on determining the accuracy with which movable-bed models repeated bed configurations under exactly the same conditions of operation. Test data from nine models indicated that substantial variations occurred, especially in models with long periods of operation and which simulated deep pools. Project engineers subsequently recommended discontinuing the construction of such models until the sources of error were identified. Several theories blamed model shortcomings on such elements as fixed banks, poor operating techniques, and the presence of algae.[12]

A second test series, performed in 1935, confirmed the findings of the first investigation but also could not clearly identify specific causes of error. Elimination of algae was of no help and variations in operating techniques produced little difference in accuracy of reproduction.[13] Falkner, in a re-evaluation of policy, concluded that any improvement in model accuracy would involve major changes either in design or operating methods, and that the fundamental concepts of movable-bed studies required further analysis.[14]

Model Improvements

In 1935 Falkner initiated a more comprehensive investigation of model methods and theories along three distinct lines:

- an evaluation of the mechanical features of model construction and operation,
- a search for better bed materials for movable-bed models, and
- a reanalysis of theories of hydraulic similitude.

Surveys of mechanical features disclosed a lack of uniformity in construction methods and even more diversity between individual model operators and experiment groups. Falkner then drew up a set of mandatory procedures and established an independent mechanical design section to investigate, improve, and standardize mechanical appurtenances. Procedural changes included requiring a section inspector and labor foreman to be present with molding crews of movable-bed models at all times, standardization of weir sizes, and introduction of improved instruments and automated systems. Model construction and operation thereafter, Falkner believed, improved on a continuing basis as refinements were incorporated into practically every succeeding model as it was built.[15]

Bed materials for models had long been a source of controversy. Materials such as sands taken directly from a prototype often produced different results in a model than in nature. Observations of early movable-bed tests indicated that riffles formed in model beds that would not occur in the prototype were a principal source of inaccuracy. Further experiments in 1934 and 1935 indicated that sand grain diameter, roughness, and other factors strongly influenced formation of riffles, waves, and dunes in flumes.[16]

St. Johns River model incorporated substantial improvements as modeling progressed in the mid-1930s

Through 1935 and most of 1936, Falkner supervised an attempt to develop a synthetic sand mixture that would move in models without the formation of riffles. Of 60 materials considered, including clays, coals, slag, resins, haydites, and gilsonites, only 23 were found suitable from an investigation of their physical and chemical properties. Availability, cost, or similarity to other materials reduced the number to eleven, which were then tested in flumes. Four emerged as primary candidates for practical model use: gilsonite, a limed resin, a Kansas coal, and haydite. All were lightweight and could be moved without forming riffles in models with less distortion than previously required.[17]

Responsibility for appraising the state of the art in hydraulic similitude fell largely to Lieutenant Kenneth D. Nichols, who served as Falkner's Assistant Director from September 1935 to June 1936. Studies at Cornell University, the University of Iowa, and in Europe preceded Nichols' experimental work at the Station. His conclusions, expressed in a series of memoranda, emphasized that vertical and slope distortion in many previous models had been too great, a conviction long shared by Falkner.[18] WES models then tended to incorporate smaller distortions with other improvements. By 1937 Falkner was convinced that great progress had been made in model construction and operation since his appointment as WES Director, but that further refinements must continue.[19]

Field Verification of Model Studies: Successes

A survey of Corps districts for which WES had performed model work marked the culmination of Falkner's attempts to compare model predictions with field results. He personally visited 12 districts in May 1937, gathering data on field verifications of 14 projects executed with older models and three projects performed with improved versions. Results, even with older models, were generally satisfactory. Eleven of the 14 executed projects showed close parallels with model predictions, although the other three displayed distinct variance. Two of the three more recent projects demonstrated decided tendencies to follow model behavior. The third had not been in operation long enough to provide meaningful data. Perhaps even more encouraging, interrogation of

Mississippi River Island No. 9 dike evaluation model and shed and in action, 1934

Port Washington Harbor, Wisconsin, breakwater model

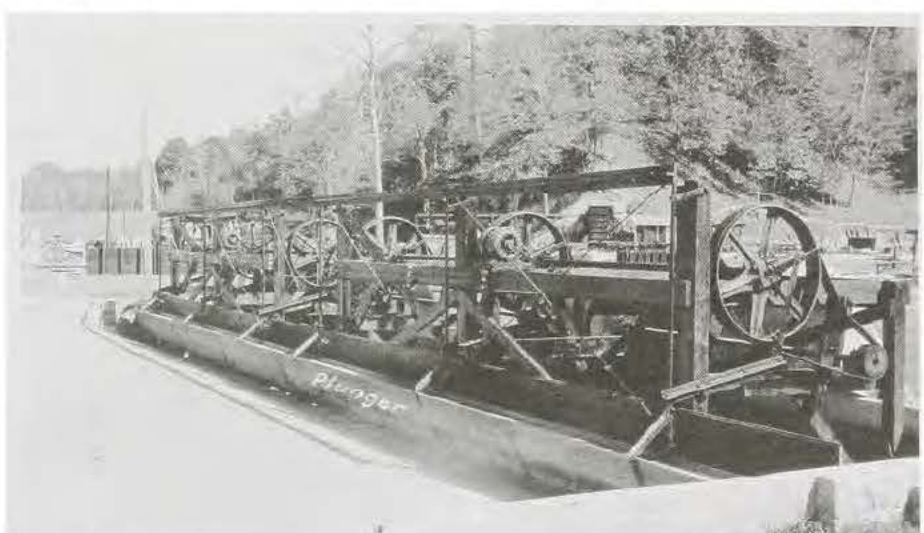
approximately 40 engineers in the widely scattered districts disclosed a unanimous opinion that hydraulic models were a great aid to design engineers and that model tests should be made a part of the regular design procedure when time permitted.[20]

Of the 11 successful projects dating from the Vogel era, six dealt with river regulation, such as the dike evaluation at Island No. 9 on the Mississippi River. Vogel had reported on all six in glowing terms in the ASCE *Proceedings* in 1935, and Falkner's 1937 investigation reinforced the former's claims.[21] Other successes included design of a dike system to improve navigation on the Savannah River below Augusta, GA; measures to improve a jetty channel at Brazos-Santiago Pass, TX; prevention of shoaling at Starved Rock Lock and Dam on the Illinois River by closing a breach; and design of spillways for the St. Lucie Canal in Florida.[22]

In an unusual twist, the District Engineer in charge of a project at Port Washington Harbor, Wisconsin, rejected findings of a WES model study to his own detriment. The study evaluated a proposal to extend a breakwater to narrow the harbor entrance and reduce the height of storm waves within the harbor. Although the WES report recommended against extending the breakwater and advised that better, and cheaper, results would accrue from wave-absorbing cribs within the harbor, the district proceeded with its plan. Storms continued to damage docks and boats in the harbor and studies showed that wave heights had not been sufficiently reduced. However, wave-absorbers built by private parties at one end of the harbor, similar to those the WES study suggested, appeared to be of great benefit. Falkner thus considered the WES experiment verified.[23]

Field Verifications: Failures

The most obvious failure of a WES model to predict behavior in a prototype was the project for the new entrance canal at St. Andrews Bay. While the model predicted that the older channel would completely shoal up, no such shoaling occurred. The model also indicated that the new channel would become 3,700 feet wide, yet it expanded to



Wave machine used in early harbor studies


Mississippi River Head of Passes model

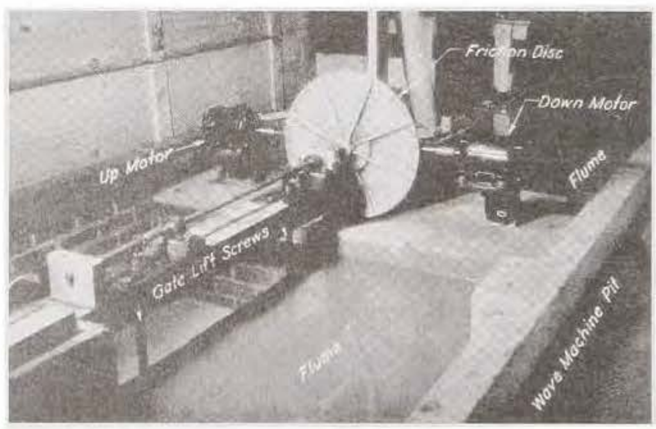
only 800 feet Falkner concluded that the model's failure indicated an inability to properly simulate tidal currents and waves.[24] It was evident that harbors and tidal estuaries would present special challenges to future WES model studies.

Another instance of model failure involved the Head of Passes at the mouth of the Mississippi River. A series of dikes, built as a result of WES studies, failed to deepen the navigation channel at Southwest Pass. Again, the failure to accurately calculate tidal influences appeared to be the primary problem.[25]

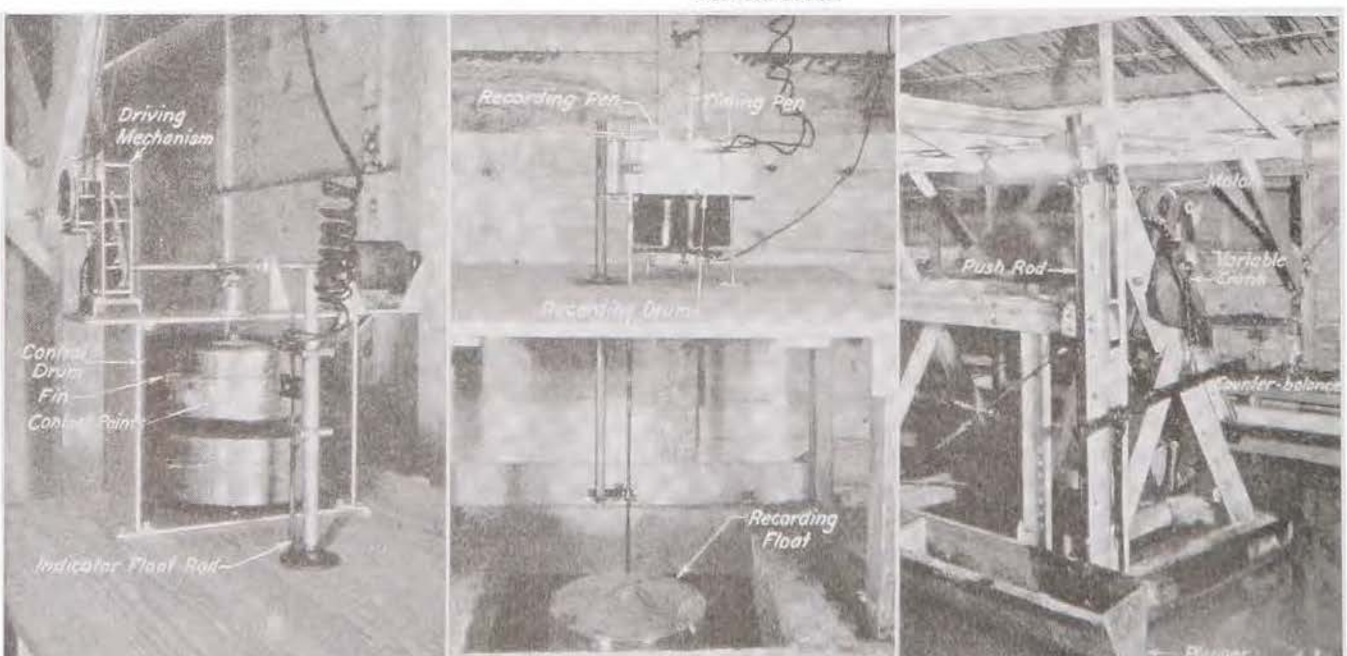
Verification of Improved Models

At the time of Falkner's 1937 survey, WES had completed only three experiments with "improved" models that could be evaluated in their prototypes. One dealt with regulation of the Mississippi River at Memphis and two with tidal phenomena — one on the Chesapeake and Delaware Canal, the other at Ballona Creek, California. All appeared successful.

The Memphis model reproduced the river reach at Memphis Depot, then evaluated nine different proposals for improving the channel. Of particular note, the model was the first to use haydite as a lightweight bed material. After WES



Ballona Creek



Ballona Creek, CA, model used a new automated tidal machine

completed experiments involving numerous combinations of dikes and dredged cuts, the Memphis District adopted the plan found most effective in the model. Although more field data would be required for complete validation, reports to Falkner indicated that the projected channel improvements were taking place with reduced maintenance costs.[26]

Both the Chesapeake and Delaware Canal and the Ballona Creek studies took advantage of a newly-developed automated tidal machine. Electrically controlled and able to reproduce the tides and currents in the prototype to the proper time scale, it represented a drastic improvement over the primitive tidal equipment used in the St. Andrews Bay study. To further improve accuracy, the two new models were housed in wooden shelters to protect them from the elements and used gilsonite instead of fine sand to simulate sediment movements.[27]

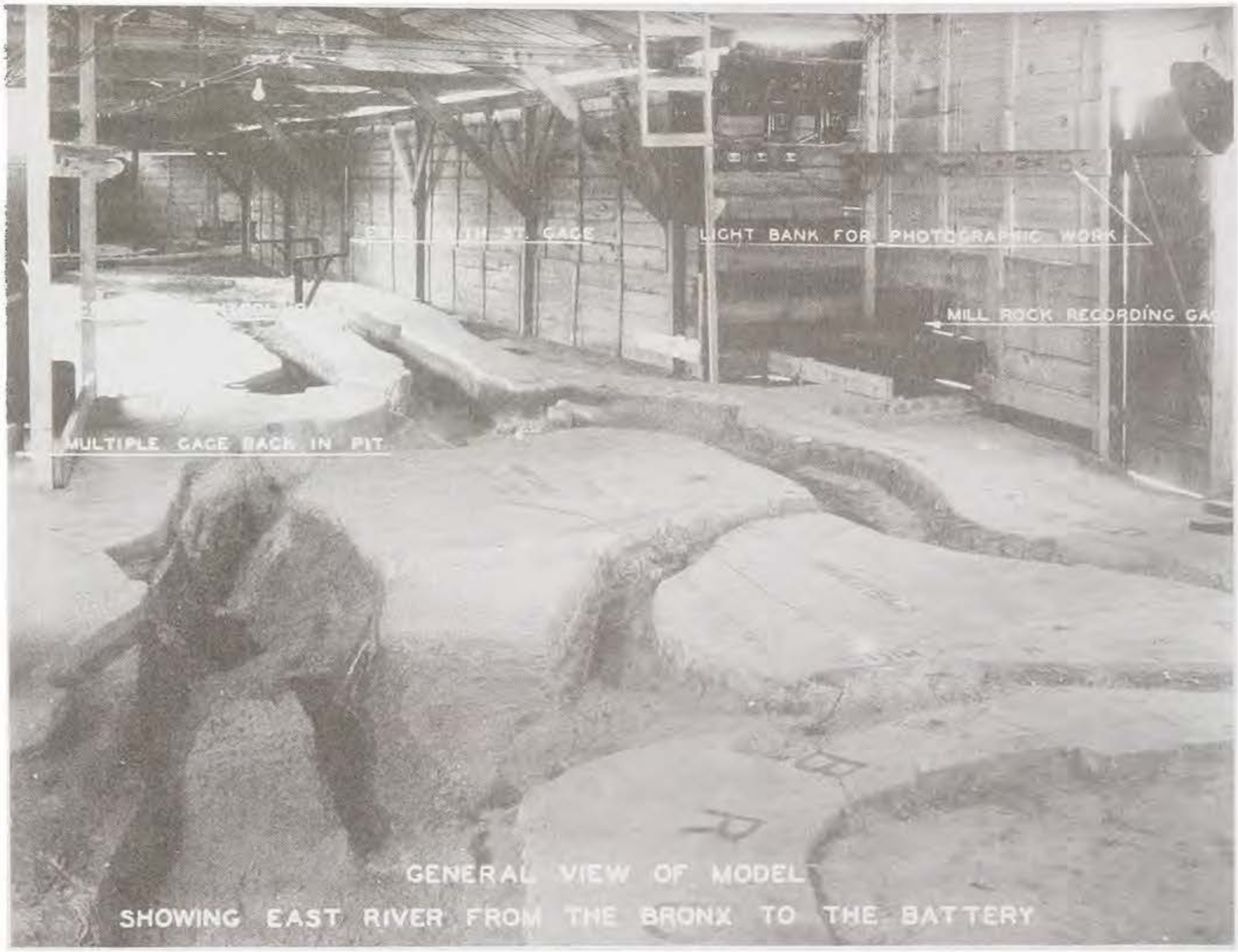
Increase in Tidal Model Projects

The Chesapeake and Delaware Canal and Ballona Creek projects reflected an growing WES role in harbor and tidal-related studies from coast-to-coast and on an international level. In 1935 the Station began an investigation for the San Francisco District involving the U.S. Navy Yard at Mare Island, California. An operational facility since the mid-1800s, the yard was connected to San Pablo Bay by Mare Island Strait. San Pablo Bay in turn formed the northern part of San Francisco Bay. The Napa River ran into Mare Island Strait slightly above the Navy Yard. The area represented a complex hydraulic system subject to strong tidal currents, freshwater currents, high winds, and heavy sedimentation.

In 1929 the Corps completed a project to increase the size of Mare Island Strait. Two miles long, 600 feet wide, and 30 feet deep at low water, the enlarged channel provided easier access to the yard for larger modern warships. The Navy also planned to expand the yard itself, with new dry-docking and docking facilities. Unfortunately, heavy shoaling in the new channel required constant dredging that was expensive and a hazard to navigation. The San Francisco District then developed several plans to eliminate or reduce dredging, and asked WES to evaluate them.[28]

Project engineers Fortson and Joseph M. Caldwell supervised construction of a fixed-bed model, housed in a specially built wooden shelter, that represented the Station's most intricate harbor engineering effort to that date. Electrically-powered tide machines reproduced elaborate currents with two high and two low waters in each daily cycle. An automated wave machine replaced the primitive hand-operated apparatus used in some earlier models. After investigating several materials, Fortson and Caldwell chose gilsonite to simulate sediments in the prototype. Experiences while verifying the model indicated that the material gave best results after being soaked in water for seven days and then kept in a mixing tank in an agitated condition. Stucco and gravel on the model bed provided necessary roughness, molded concrete or sheet metal represented solid dikes and wharves, and wire mesh screen simulated permeable pile dikes.[29]

East River, NY, model in action



East River model; note light bank for photographic work and recording gages

In 1936 WES began a similar study involving a U.S. Navy facility on the other side of the continent. Under existing conditions the Navy had full-time access to the Brooklyn Navy Yard through Lower New York Bay and the Narrows, but could use an alternate route through the East River and Long Island Sound only for limited periods at high tides. Proposals to realign and deepen the channel of the East River and Long Island Sound passage were tentative because of the powerful tides and treacherous currents in the area. Through Navy sponsorship, the New York District requested a WES model study.[30]

The Station quickly designed and built a sheltered model with appurtenances appropriate to the engineering problems of the East River prototype. It included automated tide machines, but unlike the Mare Island Strait model, wave and wind producing mechanisms were not necessary. Because shoaling was not a major consideration, experiments did not require sediment simulation. Sub-surface currents were the major concern. Project engineer John S. Gentilich injected fluorescent dyes into the model at different depths and in various tidal conditions so currents could be visually traced. Observations indicated that none of the Navy's plans for channel improvement would be effective. A second series of tests, conducted by Tiffany with the same model in 1938, evaluated other proposals. Of 23 alternatives considered, WES engineers recommended one that would cost $10 million less than the original Navy plan.[31]

In 1936 WES also began a lengthy harbor project that for the first time involved a foreign client. By 1920 Maracaibo, Venezuela, had become a major port for the export of oil, carried primarily by the Standard Oil Company. In the mid-1930s a convoy of about 25 loaded ships left the port daily, each carrying around 20,000 barrels

of oil. A large Outer Bar stretched across much of the harbor's entrance, but had not posed major problems until the advent of large, heavily laden traffic. As traffic increased, the bar grew alarmingly and threatened to close Maracaibo entirely to oceangoing ships. Ships could leave the port only at high tide, passing single file in five-minute intervals directly through a shallow and narrow channel.[32]

Model studies in the general charge of Robert B. Cochrane concentrated on determining if a new channel cut across the Outer Bar would be effective. The project was especially hampered by a lack of precise information as to tides, weather, and other conditions in the prototype area. Although completed in April 1936, the model was not considered verified until May 1938. A most unusual situation arose in that certain conditions in the prototype appeared to be caused by the propeller action of ships crossing the bar. Project engineers then designed an ingenious system in which an electrically-driven car travelled on rails above the bar in the model. Beneath the car two propellers extended horizontally into the water to within a few inches of the bed of the model. Model operators could move the propellers over any given stretch of the bar at variable speeds and in either direction desired, simulating boat traffic. Data indicated that in all cases channels in the prototype had to be maintained through continued use and dredging.[33]

Mississippi River Flood Control Model

Construction of the Mississippi River Flood Control Model in 1935 marked a monumental exception to the decline in river model engineering under Falkner. The project, in fact, surpassed any previous modeling attempt in size and complexity. Locally called "Old 94" from its job number, the completed structure modeled one of the most extensive flood-prone areas in the world. Unlike most of its model predecessors, it was not built to investigate a specific problem, but to serve as a tool to study a broad range of phenomena over an extended period of time. While earlier Mississippi

Building templates for Mississippi River Flood Control model

River models had miniaturized limited river reaches, usually bends where cutoffs were being considered, the Flood Control Model represented the entire length of the most flood-prone river section, including all areas where cutoffs might be made. This encompassed a 600-mile stretch of the Mississippi River, from Helena, Arkansas, to Donaldsonville, Louisiana (approximately River Mile 300 to River Mile 900, extending from 70 river miles below Memphis to 75 river miles above New Orleans), its backwater areas in the White, Arkansas, Yazoo, Ouachita, and Red River basins, and the entire Atchafalaya River Basin. For the first time, the model enabled Corps planners to test their flood control scheme for the entire region.[34]

Too large for the open areas in front of the WES headquarters building, crews constructed the model on a newly-acquired elevated plot extending on the east side of the original WES reservation. Its length of 1,060 feet, with a maximum width of 158 feet, forced designers to make allowance for the curvature of the earth in calculations. In possibly "the largest and quickest job of model construction ever undertaken by any laboratory," WES completed the job in only four months at a cost of $133,425. Features incorporated levees, bridges, swamps, forests, and even willow thickets. Galvanized screen, folded and turned upright in patterns determined from aerial photographs, simulated forests and thickets. Appurtenant equipment included flood lights, a telephone system, over 200 gages, five entrance and two discharge weir boxes, and a pumping system that furnished water from a new, smaller reservoir near the model. The model required 42 people to operate, and could reproduce a day's behavior of the river in 5.5 minutes.[35] (Model construction accounted for the large increase in civilian employees at WES in Fiscal Year 1935 discussed in Chapter 2. After completion of construction, much of the work force, including several sub-professional engineers, was released.)

Completed Mississippi River Flood Control model

When construction was completed, WES began a lengthy sequence of experiments dealing with floods in the prototype area. Tests concentrated on evaluating the efficiency of man-made improvements built on the Mississippi River after the superflood of 1927, including cutoffs, diversion outlets, and new levees.[36] Engineers reproduced the floods of 1929 and 1935 in the model for verification purposes before turning to the ultimate test of predicting whether the Corps' efforts over the past eight years would prevent a recurrence of the 1927 disaster. Model simulation of the 1927 flood took over 14 hours. Results optimistically indicated that, barring unexpected levee breaches, the Mississippi would indeed be held in check.[37]

Flood of 1937

Nature soon challenged the model's predictions. Severe flooding in the Ohio River Valley in early 1937 led to fears that "another 1927" was in the offing for the Lower Mississippi. For the first and only time, the Corps opened the Birds Point-New Madrid Floodway to divert part of the flow of the main stem. Nonetheless, river stages at all points from Cairo to Helena exceeded the record highs of 1913 and 1927. But below Helena, cutoffs and channel improvements lowered river stages and helped speed floodwaters to the Gulf. The Bonnet Carré Spillway diverted some of the flow above New Orleans into Lake Pontchartrain, but it was not necessary to use the Atchafalaya Floodway, as had been anticipated in a flood of that magnitude.[38]

Thompson as Director

Twenty-eight year old Captain Paul W. Thompson succeeded Falkner as Station Director in July 1937. His relationship with WES had begun in 1932 and 1933 when he served as an assistant to Vogel. After stints with the Omaha and Kansas City Districts, in 1935 and 1936, Thompson studied in Europe as a Freeman Scholar, then returned to Vicksburg as an assistant to Falkner. On Falkner's departure he took command of the Station.

Thompson abandoned Falkner's "project engineer" system, consolidating all hydraulics projects in a newly-entitled Hydraulics Laboratory with Tiffany as chief. In an organizational subdivision somewhat similar to that established by Vogel in his final year as director, the Hydraulics Laboratory consisted of three units: Experiment Section No. 1, headed by Caldwell and concerned primarily with tidal models; Experiment Section No. 2, headed by Fortson and dealing mainly with hydraulic structures models; and Experiment Section No. 3, under Vivian G. Kaufman operating only the Mississippi River Flood Control model; however, Sections 1 and 3 also handled some river models.

From left, second WES Director Captain Paul W. Thompson, Chief of Engineers Major General Julian Schley, Mississippi River Commission President Brigadier General Max Tyler, WES Executive Officer Lieutenant Doug Davis

WES: Center of Corps Hydraulic Research

Although the Station had been in operation less than seven years at the time of Thompson's appointment, he found the atmosphere to be "exciting, heady, and challenging." Numerous visitors from Corps divisions and districts came to view WES models firsthand, while scholars such as Straub of the University of Minnesota kept up a lively correspondence. As a further indication of WES primacy within the Corps, the other permanent Corps hydraulics laboratories played increasingly minor roles, with the partial exception of the Beach Erosion Board (BEB) Wave Tank at Fort Belvoir, Virginia. Thompson noted that other laboratory heads, after visiting WES, envied the Vicksburg institution because they operated on such comparatively small scales and with almost no funding.

Hydraulics Research Center

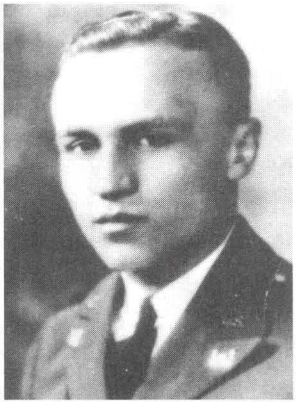
In September 1937 the Office of the Chief of Engineers initiated an attempt to better coordinate the Corps' hydraulic engineering efforts. Thompson, at OCE direction, established a Hydraulics Research Center at WES to centralize activities. The Center was to assemble experimental hydraulic data from all available sources, both domestic and foreign; to analyze and interpret such data; and to disseminate information to Corps divisions and districts. The concept was not without precedent, as OCE had already directed Falkner to establish a Soil Mechanics Research Center at WES the previous year. Its activities placed WES at the forefront of the Corps' soil mechanics endeavors. Recognizing the potential for a corresponding hydraulics unit, Falkner had recommended creation of a hydraulics center to the President of the MRC in June 1937, shortly before Thompson became Station Director.[39]

Three sections conducted the Center's functions: the Information Section, the Translation Section, and the Library, although all operated with minimal staffs. The first, under the direction of George W. Howard, collected and assembled information from around the globe including engineering periodicals, books, and engineering and project reports. All were read and abstracted so that information could be easily spread throughout the Corps. The Translation Section in 1940 alone issued 39 translations of articles on hydraulic engineering from German, Spanish, French, Russian, and Chinese sources. In addition to major articles, the section translated the table of contents of all foreign publications received at the Station and, when requested, prepared summaries of articles therein. By 1940 the Library had grown to over 13,000 items, forming probably the best collection in the United States in hydraulics and soil mechanics. Staff performed literature searches on demand and provided materials, including films and slides, for loan to Corps districts and divisions.[40]

In June 1938 the Center began to disseminate information through publication of *The Experiment Station Bulletin* (later titled *The Experiment Station Bulletin (Hydraulics)*, then *The Experiment Station Hydraulics Bulletin*). Appearing about every four months, the *Bulletin* carried feature articles, summaries of WES model work, reviews of new publications, and other pertinent data. Some issues concentrated on a specific engineering area or problem such as outlet and spillway structures.[41] Distribution extended around the world. In October 1939 the Center started a second publication, the *Quarterly Summary*, which contained data on current Corps hydraulics studies and publicized recent additions to the library. Its distribution was limited to the Corps.

Fields as Director

Captain Kenneth E. Fields succeeded Thompson as Station Director in September 1939, when the latter became Assistant Military Attaché to the U.S. Embassy in Berlin. Fields' appointment coincided with the German invasion of Poland and subsequent declarations of war on Germany by Great Britain and France. As war raged in Europe and Japanese aggression in Asia accelerated, American concerns shifted, albeit slowly, toward the impending global conflict. The Station was notably affected in that many



Captain Kenneth E. Fields

employees were members of the Army reserve and were subject to be called to active duty.

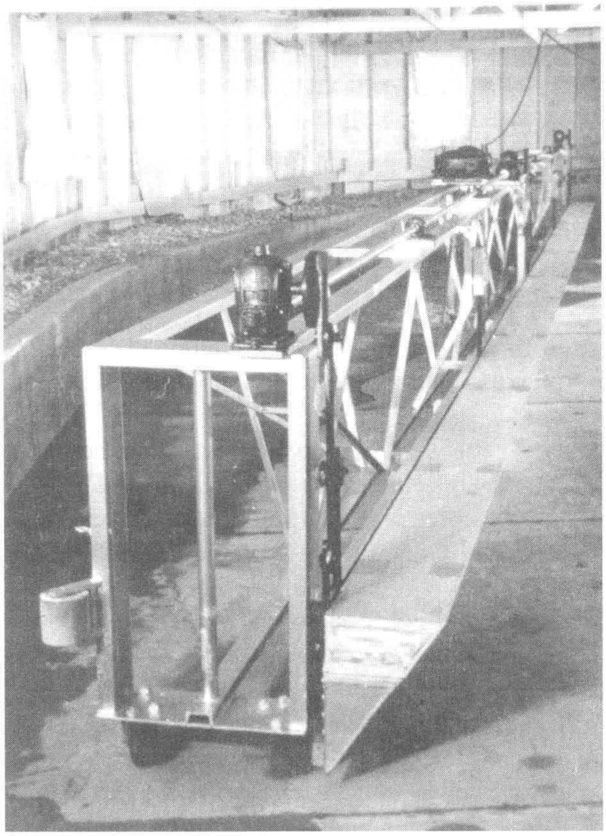
In a mild change in nomenclature, Fields renamed the Hydraulics Laboratory back to its original appellation as the Hydraulics Division. It retained that name until 1972. Tiffany remained as Division Chief. The rumblings of World War II rapidly led to further changes. In October 1940 Tiffany moved upward to become Fields' Executive Officer, replacing Lieutenant Wright Hiatt, whom the Army had transferred from WES. Station directors later changed Tiffany's title to Executive Assistant, Technical Executive Assistant, then Technical Director. As Technical Director he became the most influential figure in the administrative and technical operation of WES until retiring in 1968. Tiffany eventually earned the sobriquet "Mr. WES."

As the Division's next ranking engineer, Fortson was Tiffany's nominal successor as Division Chief, but was called into active service. In Fortson's stead, Caldwell served as Chief until transferring to OCE in January 1943. George B. "Brad" Fenwick, Caldwell's Assistant Chief, then assumed leadership until Fortson's return in 1946.[42]

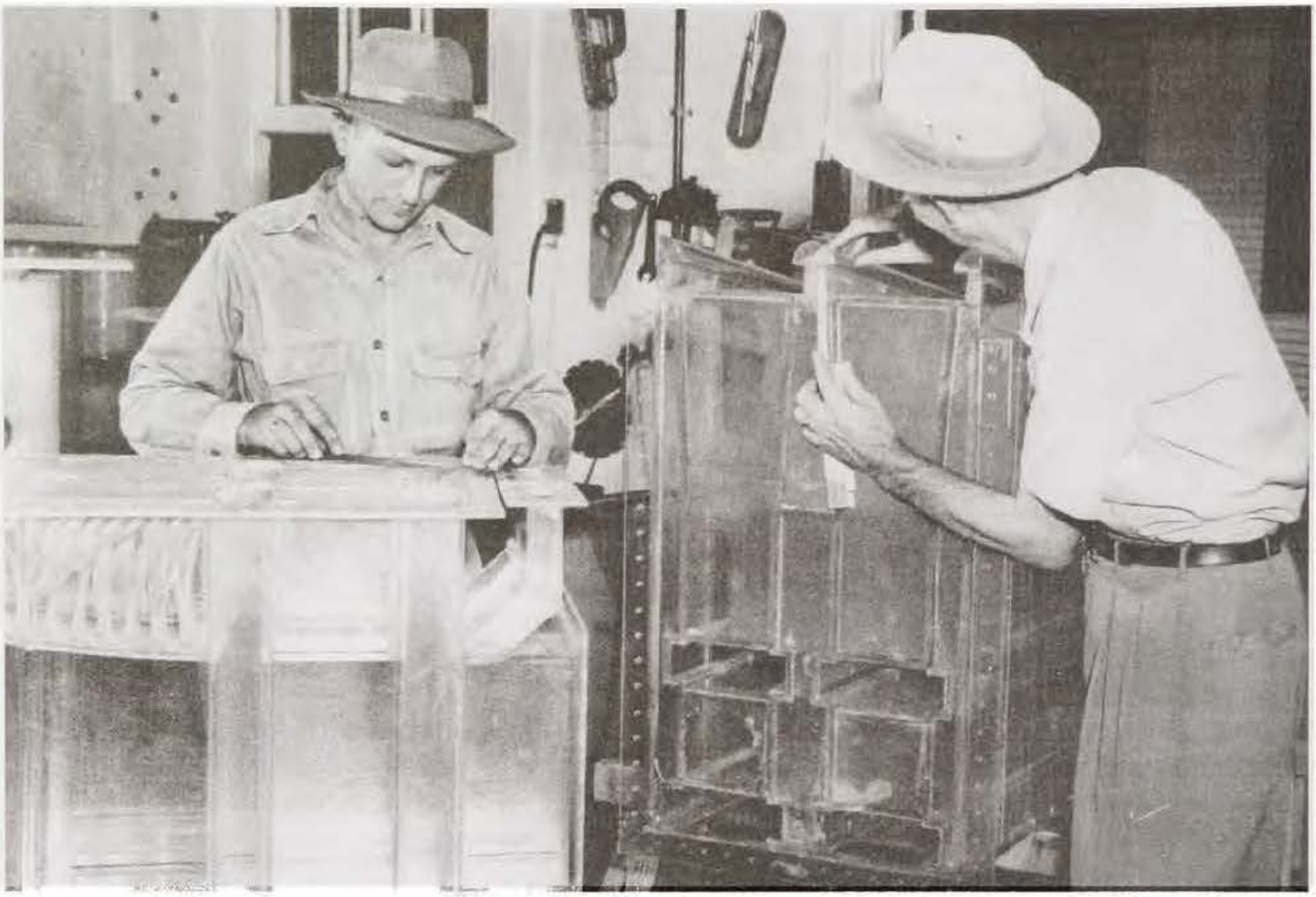
Improved Experimental Equipment

Through the late 1930s and into the 1940s, experimental equipment used in hydraulic modeling continued to improve, often through the efforts of WES engineers. This applied not only to the models proper, but to numerous appurtenances. Automated tide machines, for instance, revolutionized model studies of prototypes such as Maracaibo Bay, Venezuela; Mare Island Strait; and the East River at New York City. Related efforts with harbor models often required devices to simulate waves also. Early attempts, such as the St. Andrews Bay model, used a primitive, hand-cranked version that required a substantial amount of skill and experience to operate. By 1938, however, WES had developed a 16-foot-long rotary-type machine with a 6-inch cylinder driven by an electric motor.[43] Further advances led to the production of a plunger-type machine, also electrically driven. The newer design could be adjusted to produce any size wave at varying speeds. Compact and wheel mounted, it could be shifted easily to create waves from any direction. This was especially valuable in studies to determine the stable slopes of beaches, shores, and dam faces under anticipated wave attack, and in testing the effects of waves on breakwaters. WES wave research also led to the invention of electrical apparatuses to measure and record wave heights and pressures.[44]

For studies involving the migration and deposition of silts, WES designers devised a portable electric silt separator that made it possible to determine the quantity of silt deposited on the bed of a model without draining the model. In one



Improved wave machine, 1938



Workers making hydraulic structures models out of pyralin

continuous operation the device removed the water-solids mixture from the model, separated the water, and measured the material representing silt (normally gilsonite, haydite, or coal).[45]

Outlet and Spillway Studies

Both Thompson and Fields continued studies begun under Falkner and instituted new projects dealing with river and harbor improvement. Their tenures also saw an impressive increase in the amount of model work on spillways, stilling basins, outlet structures, and other appurtenances associated with dams. In most cases hydraulic structures models were smaller and easier to build than river or harbor models, and tended to produce very accurate data. Model replication of a spillway, for instance, normally posed no great difficulties and could be built undistorted. Also, the use of transparent pyralin to model outlet structures such as tunnels let engineers observe water flows throughout the length of the model. Prototype locations for hydraulic structures models spanned the continent, including Conchas Dam, New Mexico; Possum Kingdom Dam, Texas; Wappapello Dam, Missouri; Santee River Dam, South Carolina; Franklin Falls Dam, New Hampshire; Great Salt Plains Dam, Oklahoma; and the St. Lucie Canal, Florida.[46]

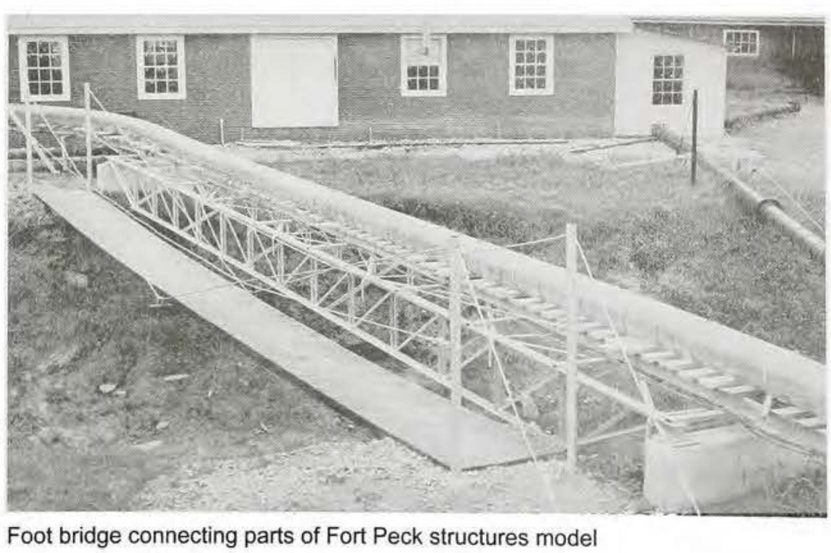
Projects for two other sites, Sardis Dam, Mississippi, and Fort Peck Dam, Montana, exemplified the Station's hydraulic structures modeling mission. Sardis Dam was to create a flood control reservoir on the Little Tallahatchie River, a tributary of the Yazoo River. Construction began in 1936. Upon completion, it would be one of the largest earthen edifices in the world, stretching some 14,550 feet. Corps planners designed an outlet structure consisting of a single large conduit controlled by four gated intakes. To predict its hydraulic performance, WES fabricated models of preliminary and final designs and conducted a series of experiments in 1937. These indicated that the original design was adequate, but led to several modifications to improve the safety, economy, and efficiency of the completed work.[47]

Fort Peck tunnel model stretched through much of the WES reservation

Subsequent model studies directed by Cochrane on two proposed Sardis spillways also resulted in design changes.[48]

Begun in 1933 and completed in 1938, the Fort Peck Dam was also a massive earthen structure. Four concrete tunnels, each almost 25 feet in diameter and over a mile long, served as outlets. On 21 September 1938 a huge landslide occurred on the upstream face of the dam, making revision of the tunnel intake structure necessary. The Missouri River Division devised two plans for remediation that OCE submitted to WES for model testing in late June 1939. Time was of the essence, and WES responded quickly. By 10 July Fred Brown had directed construction of an intake model, then supervised experiments that were completed on 2 August. Results led to implementation of the Division's first plan for remediation.[49]

Only one week after completion of the Fort Peck intake tests, OCE directed WES to perform a related study that led to design of the most elaborate hydraulic structures model at WES to that date. Corps plans called for construction of a hydroelectric plant at the outlet of Fort Peck Tunnel No. 1. Upon encountering numerous hydraulic problems, designers referred the project to WES. Model studies began in September 1939 and continued into January 1940. The earlier intake structure model miniaturized the complete interior of only one intake chamber, half portions of the two adjacent chambers, and a 200-foot-long section of one tunnel. The new model simulated the entire length of Tunnel No. 1, complete with intakes,



Foot bridge connecting parts of Fort Peck structures model

trash racks, control shafts, transitions, surge tanks, and other features. Extending 270 feet, the pyralin replica rested on an iron catwalk supported by frames set in concrete footings; passed through two buildings; and went over the Station lake's spillway exit channel on a steel truss. A cable suspension bridge provided vantage points for test personnel.[50]

Johnstown Flood Control Model

One WES study in the Thompson/Fields era involved flood control measures far from the Lower Mississippi River Valley. Johnstown, Pennsylvania, may well have been the most infamous urban area in the United States pertaining to flooding. Located in a narrow, Y-shaped valley in the Allegheny Mountains where Stony Creek and the Little Conemaugh River meet to form the Conemaugh River, the city was an easy target for flash floods. In its most spectacular, but by no means only, disaster in 1889 much of the city was already inundated by as much as 10 feet of water when the upriver South Fork Dam failed, sending a huge wall of water rushing through the valley. Out of a population of about 20,000, over 2,000 Johnstown residents were killed and property losses exceeded $12 million. Thereafter until 1913, the Conemaugh reached or exceeded flood stage annually. Civic improvements by that year raised flood stage by 3 feet, but river levels nonetheless topped the new stage 14 times in the next 17 years. After a respite from 1931 to 1935, river levels 14 feet above flood stage in 1936 devastated major parts of the business and industrial sections of the city. Although loss of life was relatively small, the municipality suffered more than $40 million in property damages.[51] At that point the city's 70,000 waterlogged inhabitants agreed that more needed to be done and, offering to put up $2 million of their own money, approached the Pittsburgh District for assistance.

By late 1937 the Pittsburgh District had devised a preliminary plan for the Johnstown area that included channel improvements, retaining walls, and other features. Hypothetically, these were to contain within banks the highest flood on record, the calamity of the previous year. The district then asked WES to perform a model study. Directed by Tiffany, Caldwell, and Fenwick, by March 1938 the Station had constructed a 250-foot-long model reproducing parts of Stony Creek, the Little Conemaugh, and the Conemaugh Rivers, with outbank areas encompassing all tracts considered subject to flooding. The effort presented an unusual challenge in that most of the model represented an urban area with numerous structures absent from the agricultural floodplains depicted in earlier flood control models. Great detail was necessary to reproduce the 27 bridges in the prototype area that, because of their inadequate openings, reduced the capacity of streams to carry floodwaters and created backwater effects. Additionally, the model incorporated the entire city street system, superimposed with city blocks outlined by strips of sheet metal placed vertically and imbedded in the model's concrete surface. Openings cut in the sheet metal outlines controlled the rate at which flood waters entered and left storage areas, while wire hardware cloth, bent into zigzag strips, simulated wooded areas.[52]

Model verification was based on reproduction of two floods for which precise data existed — the disaster of 1936 and the lesser flood of 1937 — with all channels and appurtenances representing conditions as at the time of flooding. After adjustments to improve accuracy, all bridges were removed from the model to determine their backwater effects in the prototype. Data indicated that bridges increased backwater stages from 1 to 2 feet. Model operators then tested proposed improvements to the stream channels in the model in the order in which they were to be made in the prototype. During the testing sequence, which lasted intermittently until June 1941, WES maintained close liaison with the Pittsburgh District, providing interim reports on various phases of the study as soon as data from tests were available. WES personnel also inspected the prototype area and the Pittsburgh District Engineer, members of his staff, and Johnstown city officials visited the Station on several occasions. Model projections resulted in numerous alterations to the original plan. For example, WES findings indicated that a proposed channel excavation in one section of the Conemaugh would have little benefit. Accepting

Johnstown, PA, flood control model represented an early attempt to reduce urban flooding, 1938

this prediction, the Pittsburgh District avoided removal of 200,000 cubic yards of solid rock at a savings of about $300,000, many times the total cost of the model study.[53]

Expressing absolute confidence in the project, the Pittsburgh District Engineer in late 1943 declared that Johnstown had "the largest and best channel improvement in the United States," and that "the flood troubles of the city are at an end."[54] Coincidentally, the District Engineer was none other than Herbert D. Vogel, founder of WES. Local civic leaders thereafter advertised the city as "flood free." For over three decades they were right. Unfortunately, on the night of 19-20 July 1977 more than 12 inches of rain fell on Johnstown in 8 hours. The runoff resulted in yet another spectacular flood. The town mayor described the event as "not a flood of river water, it was a flood of rain water. It was runoff." Another official noted that the city was flooded by streams that he had never even heard of.[55] At their mouths, the Little Conemaugh River and Stony Creek exceeded the record flows of 1936 by an estimated 44 percent. 87 people were listed as dead or missing, and damage estimates in Johnstown alone reached $117 million. Still, the channel project and later improvements provided enormous benefits and lessened the impact of what could have been one of the great disasters in U.S. history. Flood crests were reduced in some locations by as much as 11 feet, possibly saving hundreds of lives and preventing an estimated $325 million in damages.[56]

A Decade in Retrospect

In December 1940 WES began its second decade of research. Experiments in progress at that time represented an enormous increase in both the breadth and depth of the Station's mission. Two projects were started at the end of 1930, the indoor Ohio River Lock and Dam models and the outdoor Illinois River backwater model, and involved about twenty employees. In 1940 WES activities and facilities had expanded to include scores of personnel working simultaneously on 23 assignments. Flood control studies included the Johnstown urban model, a Mill Creek flood control project for Cincinnati, and continuous use of the Mississippi Flood Control Model for the MRC. A river navigation project for the New Orleans District looked at reducing shoaling in the Mississippi River in the vicinity of Head of Passes. Hydraulic structures research entailed design of spillways, stilling basins, outlet works, intakes, and tunnels at such diverse locations as Arkabutla Dam, Mississippi; Bayou Bodcau Dam, Louisiana; Denison Dam, Oklahoma; Franklin Falls Dam, New Hampshire; John Martin Dam, Arkansas; and Fort Peck Dam, Montana. In the rapidly developing fields of harbor, estuary, tidal, and wave studies, WES investigations ranged to Absecon Inlet, New Jersey; Richmond Harbor, Virginia; Grand Marais Harbor, Michigan; San Juan Harbor, Puerto Rico; Savannah Harbor, Georgia; and Wilmington Harbor, Deleware. Additional studies included the model study of meandering streams for the Mississippi River Commission, a major hydrological research project for the Office of the Chief of Engineers, and an analysis of pump suction chambers for the Puget Sound Navy Yard.[57] (A complete listing of WES hydraulics projects in progress in 1940, with sponsors, is included in Appendix B.) Complementing its impressive workload in hydraulics, the

WES aerial view, 1939

Station at the same time enhanced its reputation by leading the Corps' newly expanded research program in soil mechanics.[58] Efforts in both areas, however, would be dwarfed by the events of the coming years.

ASCE Hydraulics Division

ASCE structural changes in the late 1930s reflected the expanded role of hydraulics engineering in the United States. By 1938, 200 Society members had signed a petition to form an ASCE Hydraulics Division. Twenty-eight different committees of the Society were already concerned in some way with water. In April 1938 the ASCE Board of Direction voted to establish a separate Hydraulics Division to join the 11 other divisions in existence. Creation of the entity was largely the work of Fred C. Scobey, an irrigation engineer with the U.S. Department of Agriculture. Matthes of the MRC and Boris A. Bakhmeteff of Columbia University joined Scobey and two other members to form the Hydraulics Division's original Executive Committee. Four years later Matthes became WES director, while Bakhmeteff was later to serve with great distinction as a consultant to WES.

The Station's personnel played important roles in the Hydraulics Division's activities. From 14 to 19 July 1941 the Division's Committee on Hydraulic Research held one of its first conferences at WES, and in 1950 the Division conducted its premier specialty conference at nearby Jackson, Mississippi. Tiffany, Fortson, and Brown later chaired the Executive Committee, while other WES engineers and consultants served as committee members. Activities of the ASCE and other organizations enabled scholars and field engineers to make contacts on national and international levels. WES and other engineering institutions benefitted from personal relationships and the exchange of information.[59]

Notes

1. Vogel continued his stellar career with the Corps, serving as an instructor at Fort Belvoir, then as Pittsburgh District Engineer at the outbreak of World War II. In the Southwest Pacific Theater he rose to the rank of general, serving as Chief of Staff of the Sixth Army. As such, he developed logistical plans for the invasion of Leyte and the projected invasion of Japan. Postwar positions included stints as Buffalo District Engineer, Lieutenant Governor or the Panama Canal, and Southwest Division Engineer. Retiring from the Army in 1954 as a brigadier general, Vogel then served until 1962 as Chairman of the Board of the Tennessee Valley Authority. He died in 1984.

2. Falkner, *Final Report*, 1.

3. Ibid.

4. Francis H. Falkner, *Hydraulic Laboratory Projects of the Corps of Engineers*, U.S. Army (Washington: U.S. Government Printing Office, 1936), 11. Prepared for the Chief of Engineers, Falkner first presented this work to a special meeting of the American Society of Mechanical Engineers and the World Power Conference in September 1936. The following month it appeared in the ASME *Transactions*, then was published in book form by OCE in September.

5. Falkner, *Hydraulic Laboratory Projects*, 4.

6. Tiffany, V-4; Falkner, 62-64.

7. Letter, Francis H. Falkner to Lorenz G. Straub, 27 May 1935, Lorenz G. Straub correspondence file, St. Anthony Falls Hydraulic Laboratory (SAFHL), University of Minnesota, Minneapolis, Minnesota. Copy in Research Collections of the Office of History, HQ, U.S. Army Corps of Engineers, Alexandria, Virginia.

8. See letters, Francis H. Falkner to Lorenz G. Straub, 17 May 1935, and 27 May 1935, Straub correspondence file, SAFHL. Copies in Research Collections of the Office of History, HQ, U.S. Army Corps of Engineers, Alexandria Virginia.

9. Lorenz G. Straub, letters to Francis H. Falkner, 31 May 1935 and 3 July 1935; Harley B. Ferguson, telegram to Lorenz G. Straub, 26 June 1935; and Francis H. Falkner, letter to Lorenz G. Straub, 12 July 1935; Straub correspondence file, SAFHL. Copies in Research Collections of the Office of History, HQ, U.S. Army Corps of Engineers, Alexandria, Virginia.

10. Ibid., 51-2.

11. Falkner, *Final Report*, 6-7.

12. See "Model Accuracy Report No. 1," unpublished report, 1935, WES Library.

13. "Model Accuracy Reports No. 2-5," unpublished reports, 1935, WES Library.

14. Falkner, *Final Report*, 4-5.

15. Ibid., 7-8.

16. *Studies of River Bed Materials and Their Movement, with Special Reference to the Lower Mississippi River. Paper 17 of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1935).

17. See, for example, "Flume Tests of Synthetic Sand Mixture, May 1, 1936," WES *Technical Memorandum No. 95-1* (Vicksburg: WES, 1936); and "Flume Tests Made to Develop a Synthetic Sand Which Will Not Form Riffles When Used in Movable Bed Models," WES *Technical Memorandum No. 99-1* (Vicksburg: WES, 1936). Falkner in his *Final Report* mentions other pertinent WES publications such as *Technical Memorandum 103-1* which are no longer available. Falkner, *Final Report*, 10-12. Gilsonite is a variety of asphalt that occurs in the Uinta Basin of northeastern Utah. Haydite is an expanded shale or clay characterized by low unit weight, used to produce light-weight structural concrete.

18. See Kenneth D. Nichols, "Observed Effects of Geometric Distortion in Hydraulic Models," typewritten manuscript, WES Library.

19. Project reports include "The Effect of Distortion on the Content and Distribution of Kinetic Energy in Model Streams," WES *Technical Memorandum No. 96* (Vicksburg: WES, 1935); "The Effect of Distortion on the Distribution of Velocity in a Model Stream Cross-Section," WES *Technical Memorandum No. 96-1* (Vicksburg: WES, 1935); and "The Effect of Geometric and Slope Distortion on the Distribution of Energy and Tractive Force in Stream Cross-Sections," WES *Technical Memorandum No. 96-2* (Vicksburg: WES, 1936). Also Falkner, *Final Report*, 12-15.

20. Falkner, *Final Report*, 77-78.

21. Herbert D. Vogel, "Hydraulic Laboratory Results and Their Verification in Nature," *Proceedings of the American Society of Civil Engineers* 98 (1935): 57-77.

22. Details of model tests are included in "Channel Improvement of the Savannah River Between Miles 188.0 to 178.5," WES *Technical Memorandum No. 57-1* and *Technical Memorandum No. 57-2* (Vicksburg: WES, 1935); *Model Study of Shoaling Below Starved Rock Lock and Dam, Illinois River. Paper No. 13 of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1934); and *Model Studies of Spillways for St. Lucie Canal, Martin County, Florida. Paper No. 14 of the U.S. Waterways Experiment Station* (St. Louis: Mississippi River Commission, 1933).

23. Falkner, *Final Report*, 81-83.

24. Falkner, 93.

25. Ibid.

26. "Model Study of Plans for Channel Improvement of the Mississippi River at Memphis Depot," WES *Technical Memorandum Nos. 89-1 and 89-2* (Vicksburg: WES, 1936); and Falkner, 94.

27. "Model Study of Plans for the Elimination of Shoaling in the Delaware River Entrance to the Chesapeake and Delaware Canal," WES *Technical Memorandum No. 93-1* (Vicksburg: WES, 1936); and "Model Study of Maintenance Works at Ballona Creek Outlet, Venice, California," WES *Technical Memorandum No. 100-1* (Vicksburg: WES, 1936). Falkner, 75. WES *Technical Memorandum 93-2* detailed design and construction of the automated tidal apparatus, but is no longer available.

28. "Model Study of Plans for the Elimination of Shoaling in Mare Island Strait, California," WES *Technical Memorandum No. 81-1* (Vicksburg: WES, 1937).

29. Ibid.

30. "Model Study of Tidal Currents in East River, New York," WES *Technical Memorandum No. 125-1* (Vicksburg: WES, 1937); and *Technical Memorandum No. 125-3* (Vicksburg: WES, 1939). Also Brigadier General Max C. Tyler, "The United States Waterways Experiment Station at Vicksburg: Its Service for Harbour Improvement Problems," *The Dock and Harbor Authority* 25 (1944): 52-53. Tyler was President of the Mississippi River Commission and nominal Director of the Experiment Station at the time he wrote this article.

31. Ibid.

32. "Channel Improvements at Outer Bar, Lake of Maracaibo, Venezuela," WES *Technical Memorandum No. 106-1*, 3 vols., (Vicksburg: 1938).

33. Ibid.

34. A full and fascinating account, with photographs, of the construction of the model is contained in "The Construction of the Helena to Donaldsonville Model and an Analysis of its Construction Cost," WES *Technical Memorandum No. 86-1* (Vicksburg: WES, 1935). Reflecting wages and costs during the Depression, laborers made $2 per day, foremen $4.

35. Ibid.

36. See, for example, "Model Study of Flood Control Plans, Mississippi River, Helena, Arkansas, to Donaldsonville, Louisiana," WES *Technical Memorandum No. 92-1* (Vicksburg: WES, 1936); and "Studies of Existing Cut-Offs and Atchafalaya River Improvements," WES *Technical Memorandum No. 92-7* (Vicksburg: WES, 1936).

37. "Flood Control Plans on the Lower Mississippi River Using 1927 (Confined) Flood Discharges," WES *Technical Memorandum No. 92-3* (Vicksburg: WES, 1936).

38. A brief analysis of the 1937 flood is presented in George R. Clemens, "The Mississippi Meets the 1937 Flood," *Civil Engineering* 7 (1937): 379-83. Clemens was Senior Engineer of the Mississippi River Commission. Also Gerard H. Matthes, "Observations Made on Mississippi River Flood of 1937," *Civil Engineering* 7 (1937): 354-55.

39. Falkner, *Final Report*, 99.

40. See *The Experiment Station Hydraulics Bulletin* 4 (1941): 31-32.

41. For example, *The Experiment Station Bulletin (Hydraulics)* Vol. 2, No. 4 (1939) was dedicated to outlet and spillway structures, while Vol. 5, No. 1 (1942) dealt only with the Mississippi River Flood Control Model.

42. Tiffany, *History of WES.*

43. See "Model Study of Similitude in Wave Action," in *The Experiment Station Bulletin (Hydraulics)* 3 (1940): 17-18.

44. "Automatic Measurement of Waves," in *The Experiment Station Bulletin (Hydraulics)* 3 (1940) 2: 20; "Wave Model Appurtenances," in *The Experiment Station Hydraulics Bulletin* 4 (1941) 1: 21-22; also "Model Study of Wave Force Against Breakwaters; Interim Report," WES *Technical Memorandum*, unnum. (Vicksburg: WES, 1942).

45. "Model Appurtenances and Devices: Measurement of Silt Deposition," in *The Experiment Station Bulletin (Hydraulics)* 3 (1940) 2: 13.

46. "Model Tests of Conchas Dam Stilling Basin," WES *Technical Memorandum No. 105-1* (Vicksburg: WES, 1936); "Model Studies of the Spillway and Stilling Basin for the Possum Kingdom Dam," WES *Technical Memorandum No. 111-1* (Vicksburg: WES, 1936); "Model Studies of the Outlet Structures for the Wappapello Dam," WES *Technical Memorandum No. 134-1* (Vicksburg: WES, 1938); "Model Study of the Spillway for the Great Salt Plains Dam," WES *Technical Memorandum No. 148-1* (Vicksburg: WES, 1938); "Model Study of the Spillway for New Lock and Dam No. 1, St. Lucie Canal, Florida," WES *Technical Memorandum No. 153-1* (Vicksburg: WES, 1939; "Model Study of Structures for Future Power Development for the Franklin Falls Dam, New Hampshire," WES *Technical Memorandum No. 165-1* (Vicksburg: WES, 1941); and "Model Study of the Spillway for the Santee River Dam," WES *Technical Memorandum No. 168-1* (Vicksburg: WES, 1940).

47. "Proposed Outlet Structures for Sardis Dam," WES *Technical Memorandum No. 123-2* (Vicksburg: WES, 1937); and Norman H. Moore, "The Sardis Dam and Reservoir," *Civil Engineering* 9 (1939): 351.

48. "Proposed Spillway for Sardis Dam," WES *Technical Memorandum No. 132-2* (Vicksburg: WES, 1938); and Moore, "Sardis Dam," 352.

49. "Intake Structure (Plan A) for the Fort Peck Dam," WES *Technical Memorandum No. 160-1* (Vicksburg: WES, 1940).

50. "Hydraulic Characteristics of Power Tunnel, Fort Peck Dam," WES *Technical Memorandum No. 185-1* (Vicksburg: WES, 1941).

51. A detailed, and harrowing, account of the 1936 Johnstown disaster and its aftermath is included in Leland R. Johnson, *The Headwaters District: A History of the Pittsburgh District, U.S. Army Corps of Engineers*, 203-08.

52. "Flood-Control Project for Johnstown, Pennsylvania, Model Investigation," WES *Technical Memorandum No. 2-303* (Vicksburg: WES, 1949); also Joseph B. Tiffany, "Model Study Helps Prevent Johnstown Floods," *Civil Engineering* 15 (1945): 309-12. Johnson's otherwise excellent *History of the Pittsburgh District* fails to mention WES tests at all.

53. Ibid.

54. Cited in Johnson, *History of the Pittsburgh District*, 208.

55. Ibid., 316.

56. Ibid., 319.

57. See *Quarterly Summary: Engineer Department Investigations in Hydraulics and Soil Mechanics and Research Center Library Acquisitions, Period October-December, 1940* (Vicksburg: WES, 1941) for a complete listing and capsule description of all hydraulic and soil mechanics investigations in progress by the Corps of Engineers.

58. For details, see Fatherree, *The Earth Inherited.*

59. See Margaret S. Peterson, "Introduction," in Adnan M. Alsaffar, ed., *50th Anniversary of the Hydraulics Division, 1938-1988* (New York: American Society of Civil Engineers, 1990): vii; and *Descriptions of Experiment Station Work Prepared for Committee on Hydraulic Research, American Society of Civil Engineers* (Vicksburg: WES, 1941).

4 From War to Peace, 1942-1949

The Impact of War

Although in 1940 and 1941 the United States moved fitfully toward a wartime footing, nothing could prepare the nation for the shock of the surprise attack on Pearl Harbor. Almost overnight the progression from isolationism to global war was complete. For the next four years the struggle affected the lives of all Americans and their institutions. WES was no exception.

Even before open American involvement in World War II, Axis aggression in Europe and Japanese imperialism in Asia caused the United States — what Japan's Admiral Yamamoto called a "sleeping giant" — to toss and turn. Preparations for a 2-million-man Army and a greatly enlarged Army Air Corps particularly concerned the Corps of Engineers after late 1940. At that time, in a major reassignment of duties, the Army shifted the monumental task of constructing of all Army training facilities from the Quartermaster Corps to the Corps of Engineers. Many Corps officers and civilian employees engaged in civil projects then quickly changed their focus to military matters, and the Army began to call numerous Corps personnel who were reservists into active service.

Changing priorities, transfers, and call-ups profoundly influenced the Station's operations and administration. Eugene P. Fortson, for example, was ranking engineer in the Hydraulics Division after Joseph B. Tiffany became Executive Officer to Station Director Fields in 1940, but reported for active service and was transferred from Vicksburg. Tiffany later also entered the Army with the rank of captain, but remained at WES. Shortly after the United States entered the war in December 1941, Fields left the Station to serve under General Dwight D. Eisenhower in the European Theater of Operations. Tiffany served as Acting Director until the next spring when Gerard H. Matthes, Chief Engineer of the MRC and ardent supporter of Ferguson's cutoff program, assumed leadership of the Station in May 1942. A native of The Netherlands, at the age of 68 Matthes was not liable for military service. He was Director until September 1945, the first civilian director of WES.[1] (See Appendix A: Organization Charts.)

Gerard H. Matthes, WES wartime director

An enlarged military mission led Matthes to enact a structural reorganization in 1943 that split the Hydraulics Division into two separate entities: the Waterways Division and the Hydrodynamics Division. Headed by George B. Fenwick, the former dealt primarily with civil projects related to flood control and navigation, while the latter under Fred Brown conducted most military research. Within Brown's division, Robert Y. Hudson led a Wave Action Section that was especially active in military affairs (discussed later in this chapter).

War affected far more than administrative positions. The Army recognized that key engineering operations had to continue uninterrupted, so it allowed a limited number of exemptions to male personnel. Some exemptions were decided at

the Station by drawing numbers out of a hat. Nevertheless, as many engineers, skilled technicians and laborers answered the call to duty, personnel shortages developed in all facets of the Station's operation. Matthes then hired a large number of women as technicians, many of them wives of departed soldiers. According to Tiffany, WES could not have survived World War II as an organization without their contributions.[2]

Among the female technicians was Eloise H. Bodron, a 1944 graduate of Vicksburg High School. As an engineer aide, she worked primarily on the New Jersey Ship Canal model, often pacing the midnight shift on catwalks above the model. Trained "on-the-job," Bodron and other female employees were well accepted by nearly all the males, even though many had never worked in mixed company. However, some discomfort was inevitable. One particularly friendly male worker on the late shift gave unsolicited — and unrequited — serenades to Bodron "all night for a long time" before giving up.[3]

Early Military-Related Projects

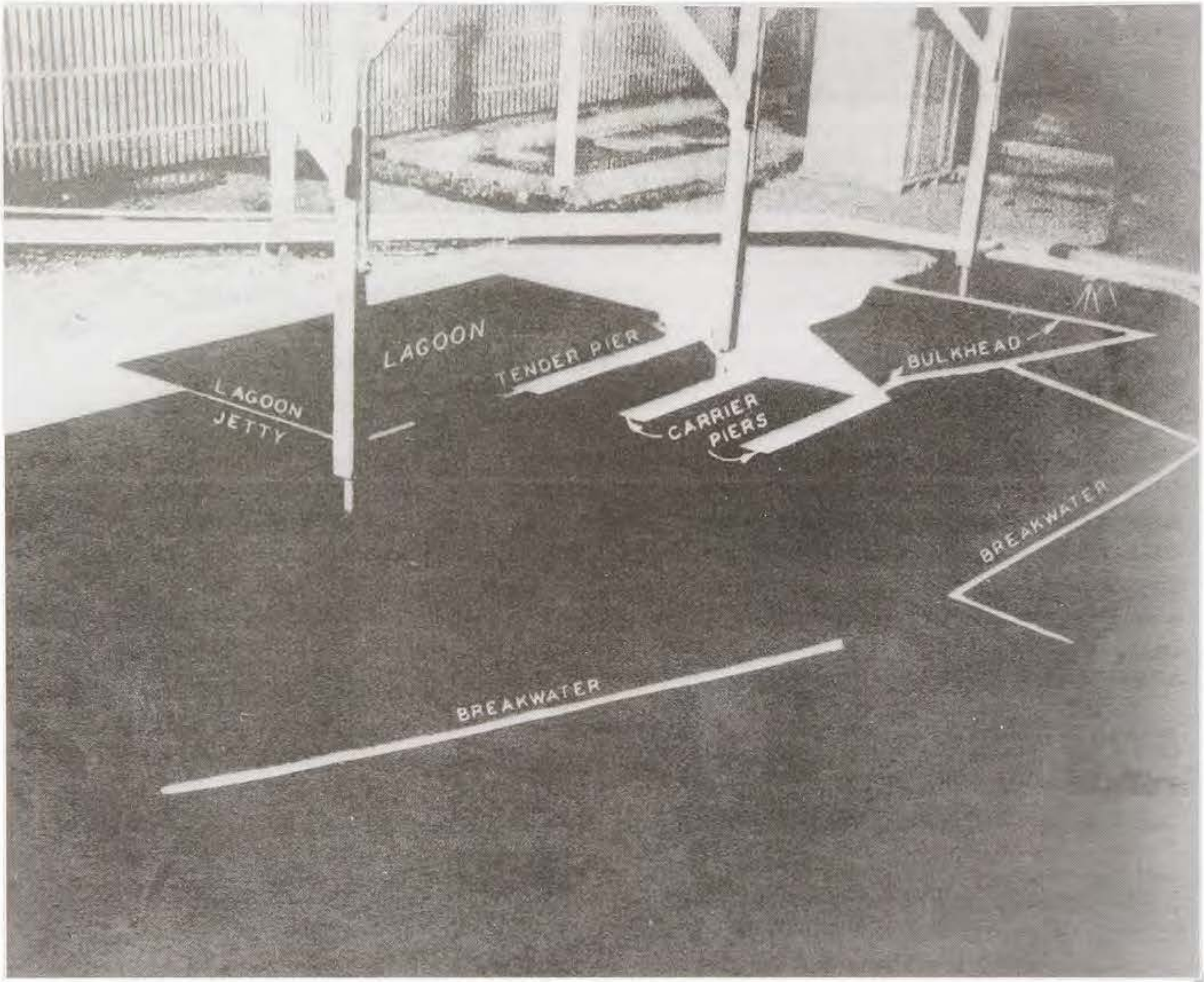
Even before World War II, a few WES hydraulics experiments had military connotations. These included the Mare Island Strait and East River studies for the Navy in the late 1930s. Also, in 1939 the Station manufactured over 100 sets of miniature pontoon bridges and sent them to military schools and training centers around the United States. There they served as the only hands-on tools for training engineer troops to erect military floating bridges.[4] A 1940 study of San Juan Harbor led to revised design of breakwaters to protect a Navy seaplane base, while a project begun in April 1941 resulted in construction of an effective breakwater system for Roosevelt Roads Naval Base at the eastern end of Puerto Rico.[5] Unsatisfactory operation of pumps in dry docks at the Puget Sound Navy Yard, Bremerton, Washington, generated a model study in which WES personnel crafted pyralin miniatures of the existing intakes and other structures. The Navy accepted WES recommendations, which were based on evaluations of six remedial plans.[6] These projects served as mere preliminaries to the hectic activities of the war years.

Wartime Research: Harbor Improvements

War-related activities dealt largely with harbor improvement for the Navy. In a notable study conducted by Brown, Hudson, and R.A. Jackson of the Hydrodynamics Section, WES devised a breakwater system for the Naval Air Station at Alameda, California. Located on the eastern side of San Francisco Bay, the base was equipped with facilities for seaplanes, aircraft carriers, and other naval ships. Installations also included a landing field for land and carrier based planes. Docking facilities consisted of a seaplane lagoon, tender pier, and a 1,000-ft carrier pier, while navigation facilities incorporated a dredged entrance channel and turning basin.

A rock seawall and rock jetty constructed to protect the base was inadequate, especially in relation to the seaplane lagoon and carrier pier. Storms on the San Francisco Bay often generated waves that damaged unprotected docking facilities and moored ships, prevented planes from landing or taking off, and made loading and unloading ships difficult. Hazardous and expensive dredging operations were also necessary to prevent shoaling in the turning basin.

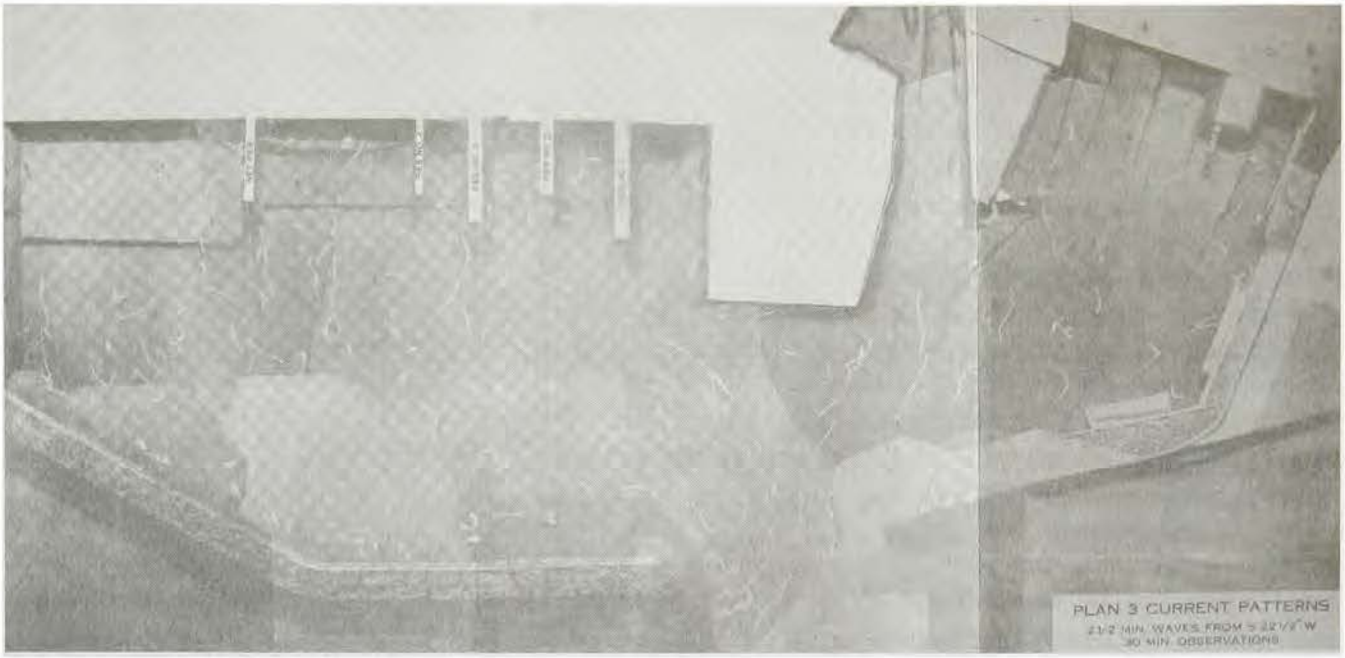
WES began constructing a model of the prototype area in November 1942, then started a series of tests that were not completed until February 1945. The model reproduced the shoreline adjacent to the Naval Air Station, the seaplane lagoon, the carrier pier, the turning basin and entrance channel, and enough of San Francisco Bay to permit accurate simulation of wave action and tidal currents. The model embodied the sum total of design methods and experimental equipment developed at WES since the late 1930s. Automated plunger-type wave machines mounted on casters simulated waves with desired characteristics from different directions of approach. A WES-designed wave-height measuring device was capable of detecting vertical fluctuations of the water surface with an accuracy of 0.002 ft in the model, corresponding to 0.4 ft in the prototype. While tide machines reproduced currents and water levels, injectors introduced saturated gilsonite into the model in the



Alameda Naval Air Station, CA, model represented one of several WES wartime harbor studies

areas from which the prototype silt material originated. During the course of experiments, WES submitted progress reports to the Navy every two weeks, and involved personnel attended several conferences in Washington, at Alameda, and at the Station. The complexity of the project required testing and analysis of more than twenty plans. WES eventually recommended, and the Navy accepted, a design that called for construction of a 6,830-ft-long breakwater that proved highly effective.[7]

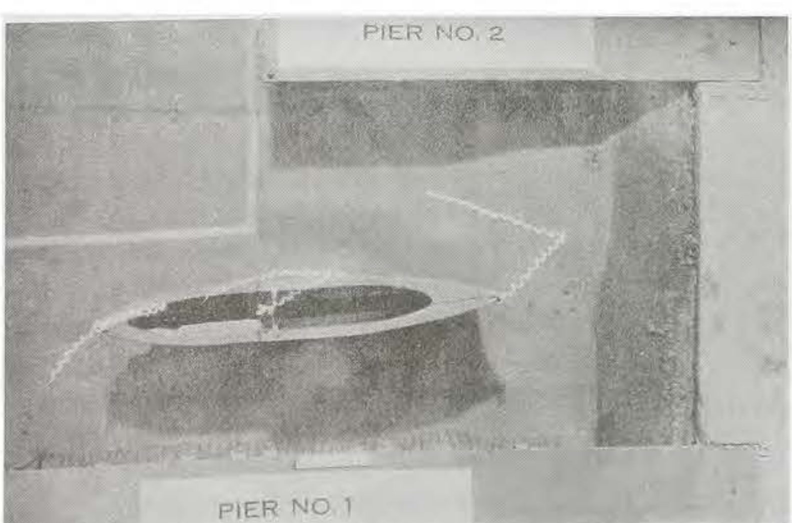
A similar project, begun in July 1943, dealt with undesirable wave and surge action at the Navy piers and dry docks at Terminal Island, San Pedro Bay, California. Despite a breakwater almost nine miles in length, wave action was such that ships moored at the piers were never motionless. At times the wave and surge action became so pronounced that moored ships collided violently with the piers, endangering the ships, interrupting loading, and causing material damage. Use of heavy anchor blocks to hold the ships away from piers were only partially effective. In less critical times such wave and surge conditions would have been undesirable, but tolerable. Loading and unloading could have been handled in dry docks rather than by the use of pier cranes. However, with the full-time use of the dry docks to provide repairs for damaged warships, this was not an option. Some damaged vessels were even moored at piers for repairs. Controlling the destructive tendencies of the harbor took on an air of urgency as the war in the Pacific increased in intensity.



Terminal Island, CA, model concentrated on reducing wave and surge conditions

Navy planners proposed construction of a large model to alleviate wave and surge conditions and called on WES to determine the best of several plans. Brown's Hydrodynamics Division designed a model about 120 ft wide and 175 ft long that reproduced all of Terminal Island, the coastline of Anaheim Bay, Los Angeles inner and outer harbors, Long Beach inner and outer harbors, all of San Pedro Bay, the San Pedro breakwater, and a surrounding portion of the Pacific Ocean. To represent details crucial to the study, it included miniature piers in the Terminal Island harbor and model ships to help determine the exact behavior of ships in the prototype. These included sheet metal miniatures of a battleship and a destroyer and a wooden battleship with a distorted linear scale. Small lights installed on the ships photographed with timed exposures provided unique charts to trace ship movements due to wave action.

The project was unusual in that the Navy, due to wartime pressures, began construction of the mole at the same time the model study began. Throughout the course of the project WES maintained close liaison with the Navy through conferences, inspections and reports. Station personnel prepared interim reports presenting the results of tests immediately upon completion of each series of related tests and also issued regular semimonthly progress reports. In designing the details and constructing the huge mole, then, the Navy used WES data almost as soon as they were obtained. Completed in September 1945, the structure was a total success.[8]



Terminal Island pier and ship models with timed exposure photos

The San Pedro Bay model found further use in the postwar period, though on a less hectic basis. Studies conducted in 1945 and 1946 led to design of protective structures for a Naval Supply Depot at nearby Point Fermin,[9] and a 1947-to-1948 project for the Long Beach Board of Harbor Commissioners resulted in further improvements in the San Pedro Bay area.[10]

A final WES wartime harbor study reached far into the Pacific Ocean. The Navy's Midway Island Operating Base, situated on Sand and Eastern Islands, was a crucial link in the chain of American bases in the North Pacific. Installations included docking and anchorage facilities for seaplanes, submarines, cruisers, and smaller naval ships, as well as landing fields for land and carrier based planes. Navigation facilities consisted of a dredged channel leading from the ocean into a mooring area in a deepwater central lagoon. Adverse conditions resulting from the combined forces of winds, waves, currents, and the peculiar physical shape of the atoll often created hazardous navigation conditions.

A Wave Action Section study, begun in November 1944, confronted a number of unusual problems. As the prototype harbor was surrounded by water rather than being located on a mainland, WES engineers reproduced it in the center of a large fixed-bed model. Furthermore, the water surface in the Midway lagoon was higher than that in the surrounding ocean, requiring design of a complex circulating system to produce the same effect in the model. Wave characteristics were complicated in that during typical storms in the prototype they averaged about 44 ft in height on the north reef but only 23 ft on the west reef. After making numerous adjustments, WES engineers verified the model and conducted tests that did not conclude until August 1946. Data indicated that the only proposal that would be effective out of the seven tested was a plan that included construction of a breakwater between the lagoon and the ocean.[11]

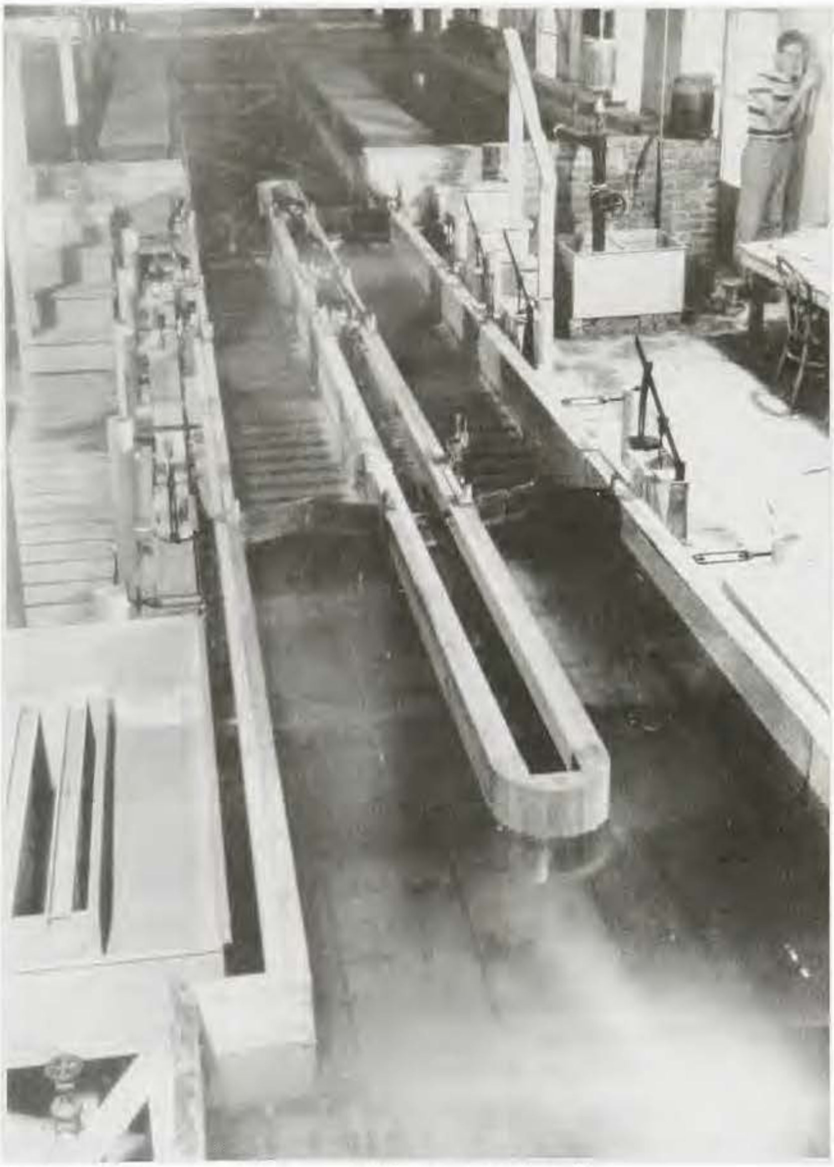
Midway Island model required a complex circulating system

New Jersey Ship Canal Study

Wartime demands often gave increased vigor to projects proposed in peace. Since 1909 Congress had authorized several investigations to determine the feasibility of a deep-draft navigation route from New York Bay to the Delaware River as part of the Miami-to-Boston Intracoastal Waterway. Numerous reports recommended a variety of canal and lock configurations that would connect Raritan Bay, the westernmost arm of New York Bay, with the Delaware about 30 miles upriver from Philadelphia. Construction of the proposed 33-mile canal would provide substantial commercial benefits in peacetime, and as the primary missing link in the Intracoastal Waterway, would protect shipping from submarine attacks in time of war.

Despite conspicuous advantages, authorities refused to proceed with construction prior to the wartime emergency. The Delaware River was the source of water for Philadelphia and other municipalities and for a large industrial region. Part of the state of New Jersey also obtained its potable and industrial supplies from groundwaters in the vicinity of the proposed canal. Intrusion of salt water from New York Bay into the canal through its locks at Raritan Bay was thus intolerable. Construction could not begin until planners were assured that saltwater intrusion could be prevented or at least held within tolerable limits.

By 1943 the Corps' New York District had devised designs for the Raritan Bay locks and plans for their operation to prevent saltwater intrusion, but could not calculate their effectiveness. The Army's Board of Engineers for Rivers and Harbors, under pressure from the U.S. House of Representatives' Committee on Rivers and Harbors to make recommendations as to


Raritan Bay locks model involved WES in early lock studies

excessively. Salt water, with a higher specific gravity, tended to stay at the bottom of the locks where it was effectively removed by a system of valves and flushed with fresh water.

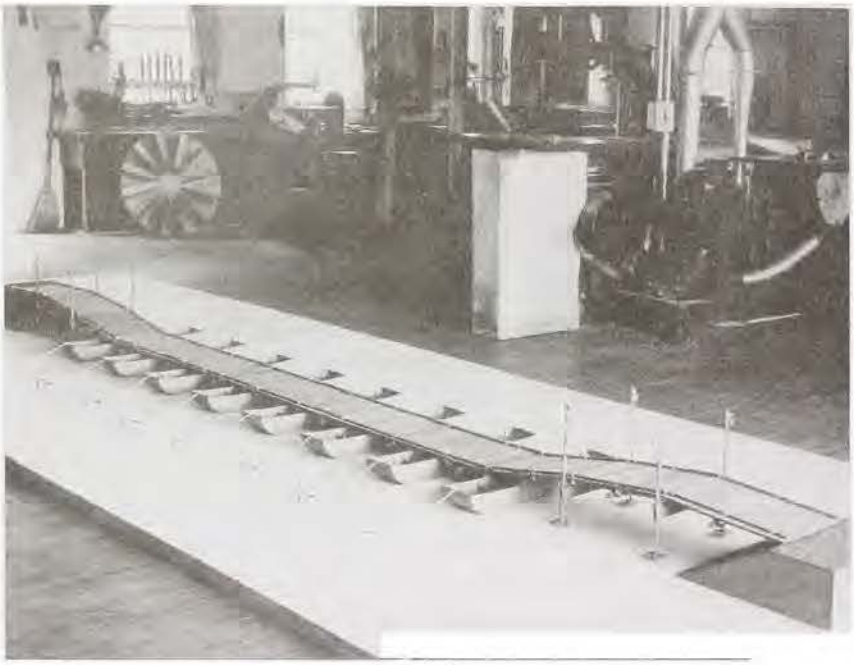
As in a number of wartime projects, WES engineers maintained close contact with involved parties throughout the course of the studies. Representatives of the New York District inspected the models from time to time, while WES submitted reports as various phases of the study were completed. Reflecting the magnitude of the project, conferences held at WES, in Washington, D.C., and in New York City included personnel from the Station, OCE, the Board of Engineers for Rivers and Harbors, the North Atlantic Division, and the New York District. On one occasion representatives of local interests of the states of New Jersey and Pennsylvania also made the long trip to Vicksburg to personally examine the WES models and confer with Corps officials.[12]

Despite optimistic WES test projections and support for the canal by many commercial and political interests, postwar priorities shifted away from construction. Prohibitive costs for limited benefits discouraged economic planners, while the slim possibility of submarine attacks in the near future neutralized military arguments in favor of the project. The canal was never built. Failure to construct the prototype, however, did not negate the value of WES experiments, as they served as a basis for future studies and provided general data for related projects.

whether to proceed with the project without modifications, called for model studies. The Chief of Engineers subsequently authorized WES to commence investigations in December 1943. Tests began in January 1944 and continued until May 1945. Brown, Henry B. Simmons, Buford C. Keene, and John W. Bolin, Jr., supervised construction of three models of the proposed locks to different scales and used each to study specific problems. Particular care was taken to insure that the salinity of water used in the models was the same as in the prototype. To differentiate between fresh and salt water in the model, test designers tinted the latter with green dye. Experiments indicated that fresh and salt water, when introduced into the locks in the manner intended in the prototype design, did not mix except when stirred

Pontoon and Pneumatic Float Development

In studies unrelated to navigation, the Hydrodynamics Division directed a project aimed at improving pontoons and pneumatic floats used in



Pontoon bridge model

be prevented by an improved bow design or, possibly, with attachments to the existing design.

WES first made the models of current American, British, and German pontoons entirely of a plastic which closely simulated to scale the effect of skin friction between the pontoons and the water. About 4 ft long, the models included all outside details of the prototypes such as handrails and skids that might affect hydrodynamic flow. Engineers anchored the models lengthwise in a 4-ft-wide flume and placed lead weights within them to represent loads up to nearly 35,000 pounds. This left a freeboard of only about 6 inches on the American prototype. Water coursing through the flume simulated a 20-ft-deep river flowing at measured and regulated velocities. Data indicated that the American pontoon could carry heavier loads than its British or German counterparts in low-velocity flows, but performed poorly in high-velocity flows such as those likely to be encountered in Europe. WES then tested the American version with twelve different attachments to the bow designed to improve buoyancy. Another test sequence evaluated four new pontoon designs. Since new designs showed no significant improvement over attachments to existing pontoons and would be more difficult, expensive, and untimely to manufacture, WES recommended adoption of a windshield type attachment until time permitted development of an adequate replacement.

As in the simultaneous Terminal Island breakwater investigation, Hydrodynamics Division personnel maintained contact with contracting authorities through progress reports, interim reports on results of certain tests as soon as they were completed, and visits to WES by members of the Corps' Engineer Board. By 1944 the Army was fabricating improved pontoons and pneumatic floats based on WES data.[13]

the construction of floating military bridges. Army planners considered the venture urgent. Already looking ahead to the liberation of Europe, an invasion of Nazi Germany appeared imperative. Such an operation would require forced crossings of numerous rivers which, because strategists anticipated that no permanent bridges would be left standing, must of necessity be on temporary floating bridges. The notoriously swift and treacherous rivers in the European Theater of Operations, notably the Rhine, presented formidable technical difficulties.

Under Bolin and Brown, who doubled as Acting Chief of the Hydraulics Structures Section as well as Division Chief, WES crews assigned to the pontoons/pneumatic float project worked around the clock seven days a week from June until November 1943. Tests concentrated on development of an attachment for the bow of the standard U.S. heavy type pontoon, determination of the best bow shape for future pontoons, determination of the most effective means of anchorage, and improvement of the upstream bow shape of pneumatic floats. Bow shapes were crucial in swift currents. When heavily laden, pontoons had little freeboard — the distance from the top of the ponton to the water surface — at their bows and sides and could be overtopped. Army designers anticipated that overtopping could

Ponton bridge in action, World War II

In addition, the Army constructed full-size prototypes for field tests of the four new pontoon designs evaluated at WES. A version promoted by the Stevens Institute of Technology with a streamlined bow appeared most promising. Unfortunately, tests conducted by the Corps' Engineer Board in swift water at the Desert Test Section at Yuma, Arizona, exposed serious drawbacks. When placed side by side and with normal spacing, waves from the bows of adjacent pontoons caused a buildup of flow between pontoons that overtopped the sides. WES then conducted a second series of model tests in 1945 and 1946 in an attempt to improve the original design. Test personnel discovered that plastic models, such as used in the first series of tests, failed to reproduce prototype deflection characteristics when used as supports in typical four-pontoon or seven-pontoon rafts. Later models were made of thin zinc sheeting that was light in weight, easily fabricated, and more accurately reproduced conditions in nature. Also unlike the first experiment series, later model tests used four or seven ponton units secured abreast as a single raft. Again, WES efforts led to revisions of the bow design, although these features were not incorporated into prototypes until after World War II.[14]

D-Day Breakwater Tests

By the summer of 1943 Allied leaders began making concrete plans for the invasion and liberation of continental Europe. The selection of Normandy as the landing site offered the strategic advantage of surprise, but presented momentous engineering problems. First and foremost, U.S. and British strategists concluded that French harbors in the invasion area would not be able to handle the massive flow of traffic necessary to supply and reinforce Allied armies after a beachhead was established. In a calculated gamble, engineers decided to construct two great artificial harbors, a feat upon which the success or failure of the invasion might well depend.

Code named "Mulberry," the harbors were to consist primarily of huge breakwaters, built offshore with giant concrete caissons, and floating roadways called whales leading about 3,000 ft from the caissons to the shore. Since no data existed concerning the engineering behavior of caisson breakwaters in field conditions, OCE, in September 1943, ordered WES to perform a model study. Specific information was needed concerning the wave and tidal pressures exerted on the front and back faces of the proposed breakwaters, the stability of breakwater sections with respect to overturning and sliding, and the movement of bed materials beneath and around the structures. Another series of model tests, conducted concurrently by the Corps' Beach Erosion Board (BEB) at Fort Belvoir, Virginia, concentrated on the caissons' towing and sinking characteristics. British engineers performed parallel investigations.


"Mulberry" caisson model used in D-Day preparations

Both the Navy and OCE developed breakwater designs. Tests on the OCE model, a triangular-shaped structure, were not encouraging, so efforts concentrated on the Navy version. The prototype was to be 61 ft high, 60 ft wide, and 160 ft long with semicircular ends. Walls were to be 1-ft-thick reinforced concrete. Transverse walls extending from bottom to top divided the open-topped interior into compartments, with each transverse compartment subdivided by ribs. When filled with water and sunk, engineers hoped the edifices would provide protection against the elements and serve as platforms to unload ships.

Brown and Hudson supervised hydraulic tests while Eugene H. Woodman devised measuring and recording devices. First they designed wood and steel models of the caissons, each slightly over 5 ft long and 2 ft high and weighing 365 pounds. An indoor wave tank 18 ft wide and nearly 120 ft long served as the testing facility. Its floor declined slightly seaward from the model shore to exactly reproduce the sloping bottom of the Normandy coast. Working on a seven-days-a-week, 24-hours-a-day schedule through the fall of 1943, a project group subjected models to a wide variety of wave conditions, scour, and other phenomena likely to be encountered. For security reasons, personnel were not informed of the use to which the caissons would be put. Nevertheless, Tiffany later claimed that he had figured out the purpose of the breakwaters and the location they were to be used by studying tidal specifications.[15] In any case, data indicated that ballast such as sand would be necessary to prevent the caissons from rocking and settling into the bed material.[16]


Caisson model in action

Invasion planners considered the project to be of such urgency that written WES reports were not required. Brown, in fact, called OCE on an almost-daily basis to report test results as soon as they were observed. OCE then relayed data to England, where caissons were to be constructed. Tests at the Station ended in December 1943, even though incomplete, because British builders were forced to proceed with prototype construction as expeditiously as possible for the impending invasion. Early in 1944, British engineers, with WES data at their disposal, finalized designs and began construction of about 150 caissons. These were towed across the English Channel in the aftermath of D-Day to form the anchors of the Mulberry harbors. Although a severe storm totally destroyed one of the harbors within a matter of days, the other stood as one of the great engineering marvels of World War II, capable of handling at least 12,000 tons of equipment and 2,500 vehicles a day.

The WES role in the design of the Mulberry breakwaters has been a matter of historical controversy. Tiffany in his 1968 *History of the Waterways Experiment Station* noted that "Chief among the projects undertaken during the war [was] the study of the stability of artificial harbor breakwaters designed and constructed for the 1944 Normandy invasion."[17] Gordon A. Cotton stated 10 years later in *A History of the Waterways Experiment Station* that

> *Two artificial harbors tested at WES, then built in secrecy and towed across the English Channel behind the assault forces for installation on the Normandy beaches, were used to furnish supplies to the invasion armies and, according to a statement from Supreme Allied Headquarters, "made possible the liberation of Western Europe."*[18]

Lee F. Pendergrass in a 1989 unpublished manuscript echoed this sentiment, adding that "Perhaps the greatest strategic contribution of the Hydraulics Laboratory [sic] was the testing of two artificial harbors...used in the invasion of Normandy." He nonetheless noted that "the portable harbors ended up being designed by the British," with WES providing the "essential guidelines."[19]

WES work in fact appears to have had little, if any, impact on caisson breakwater design and none at all in the design of the Mulberry harbors as integrated wholes. Rear Admiral William H. Smith, Director, Planning and Design Department, U.S. Navy, wrote in June 1945 that American input was minimal, stating that both the British and American navies prepared complete caisson designs, but that the design adopted was "the basic British design which did, however, incorporate some of the features of the [U.S.] Navy design."[20] Use of WES data was not acknowledged by the British.

Fittingly, WES personnel directly involved with the breakwater project did not make grandiose claims. Hudson, in an article for *Civil Engineering* in September 1945 asserted that "The caissons used for protection of the D-Day harbors were of British design and were not identical with those used in the [WES] model tests."[21] Most Mulberry caissons were substantially smaller than American designs tested at WES and had squared rather than rounded ends. Perhaps Station engineers derived some grim satisfaction in that, had British designers taken their advice to strengthen the structures and add ballast to prototypes, destruction of one of the harbors by a storm could possibly have been averted.

Other WES Connections in the European Theater

Several WES employees served in combat roles in the European Theater of Operations, including two former Directors. Paul W. Thompson, WES Director from 1937 to 1939, commanded the Assault Training Center in England from April 1943 until March 1944. In preparation for the invasion of Europe, the Assault Center was to insure that both infantry and engineer contingents who would spearhead the assault were properly prepared. Through the spring and summer of 1943 Thompson and his staff studied the French coastline, calculating that at no place along the coast of northwest France could the Germans use more than one platoon per 2,000 to 2,500 yards to protect beach fortifications. They predicted that the enemy would have strong field defenses with

concrete pillboxes and other emplacements, but with relatively thinly spread defenders providing automatic weapons fire. D-Day planners consequently prepared — correctly — for this scenario, and Thompson's center readied units to deal with such a defensive scheme. Quite familiar with the value of modeling, Thompson's engineer units constructed and placed modeled beach and underwater obstacles for training purposes and gave lectures to commanders on a number of subjects connected with the coming landing. Thompson landed in Normandy at approximately 7:30 a.m. on D-Day and was promptly seriously wounded.[22]

Kenneth E. Fields, Thompson's successor as WES Director from 1939 to 1941, also served as a combat engineer through the Western European campaign, playing a key role in the Allied invasion of Germany. In March 1945, Allied units prepared to cross the Rhine River, Germany's last great defensive barrier in the West. As anticipated, German engineers attempted to destroy the Rhine bridges and were successful with one exception: their efforts to demolish the bridge at Remagen resulted in major structural damage but left the span intact. Captured by the U.S. Army on 8 March, it provided a conduit for men and materials to cross the swollen river for several days. On 17 March, however, while Army Engineer troops attempted to make repairs, most of the bridge collapsed. Fields, who had risen to the rank of lieutenant colonel, supervised reconstruction of the now-historic site.[23]

Simultaneously at other locations, American forces were crossing the Rhine on pontoon bridges whose designs had been improved by WES tests. To aid these units, the Corps of Engineers established a river stage and flood prediction service for the Rhine and its tributaries. Flash floods or other rapidly fluctuating river stages could potentially wreck tactical bridges unless some advance warning was given. Since precise information on the Rhine was lacking, Corps personnel culled data from all available sources. In November 1944 the WES and MRC libraries contributed German atlases that gave widths and depths of the Rhine at a number of locations, 24 sheets of hydrographs showing actual river stages at half a dozen critical points, charts with information about rainfall at various points along the Rhine, and a temperature chart showing the variation in temperatures for a selected year. Combining this with information from other sources, the Corps on 16 March 1945 — one day before the collapse of the Remagen bridge — began broadcasting forecasts over Radio Luxembourg giving 48 hour predictions of river stages. By enabling field engineers to plan and prepare with up-to-date information, the forecasts helped make the Rhine crossings a complete success.[24]

The tradition of WES accomplishments in hydraulic modeling played one other role, albeit indirect, in the Rhinelands operations. In 1943 American forces had captured a German army staff study that contained a lengthy analysis of the military aspects of German rivers, including plans for the use of man-made floods to hinder troop movements and destroy temporary bridges. Using these tactics in early 1945, German engineers intentionally flooded the Roer River valley, postponing an Allied crossing for nine days. The Rhine presented more portentous opportunities. Nine dams on the Upper Rhine impounded millions of cubic ft of water that could be released either by destroying the dams or by lowering their gates. In the latter case, floods could be repeated as soon as reservoirs refilled.

Early Allied attempts to theoretically calculate the magnitude of flood waves on the Rhine were of little use. Corps officers in Europe subsequently commissioned the French experimental firm of Neyret-Beylier et Picard-Pictet to build a model of the Upper Rhine, complete with dams and other structures. Supervised by Brigadier General Henry C. Wolfe and Major Albert J. Nowicki on a 24-hours-a-day basis, French workers completed the project well in advance of time estimates despite shortages of materials and manpower. The 700-ft-long replica assisted tacticians in selecting assault crossing and bridging sites, assembly areas, dump locations, and sites for other installations where they would be least affected by inundations. Although WES was not directly involved, the Station's successful use of models over the preceding 14 years was a primary factor in ordering the study. Lieutenant Colonel Stanley W. Dziuban of OCE, in recapping the project, stated in 1946 that the Rhine model was

General view of Upper Rhine River model, Grenoble, France

Although undoubtedly unprecedented in the annals of engineer field operations, such hydraulic model experiments have been a standard technique of the American Army Engineers at the U.S. Waterways Experiment Station at Vicksburg, Mississippi. Their use in the Rhine Campaign furnishes an excellent example of how Army Engineers are able to make their peacetime and wartime functions complement each other, resulting in improved execution of both.[25]

Mississippi Basin Model

Construction of the Mississippi Basin Model (MBM) — the largest and most complex hydraulic model ever built — had an unexpected war-related connection. Major Eugene Reybold, while serving as Memphis District Engineer during the 1937 flood, conceived the idea for a comprehensive model of the entire Mississippi River basin. Models of limited reaches of the river and its tributaries, such as the Mississippi River Flood Control Model, had been invaluable tools for predicting flood levels and in providing data for remedial actions. Still, Reybold felt that flood control problems in the Mississippi River Valley could be dealt with even more effectively through use of a much larger model, one that incorporated the whole 1,250,000 square miles of the basin, which includes parts of 31 states and two Canadian provinces. Only a model of that dimension could reflect the total hydraulic behavior of the great river and tributary system, with its levees, floodways, cutoffs, reservoirs, and other interrelated flood control mechanisms.[26]

Upon becoming Chief of Engineers in 1941, then-Lieutenant General Reybold pushed to make the model a reality. In May 1942 he met with Matthes and Tiffany in Washington for discussions and directed them to conduct a preliminary study as to the feasibility and practicability of constructing such a huge facility. The WES study, transmitted to Reybold in October 1942, encouraged that construction begin, but with several alterations to Reybold's original plan.

In April 1943 the Station submitted a detailed project report complete with cost estimates and a timetable for construction that incorporated these alterations. The proposal called for a huge model built with the same numerical scales as those of the Mississippi River Flood Control Model. It would cover approximately 200 acres, reproducing all existing and proposed flood control reservoirs, as well as levees, dikes, floodwalls, floodways, and other works. The network of streams — 15,000 miles long in the prototype — would be nearly eight miles long in the model. In the meantime, since Reybold was aware that personnel and materials were in short supply and that civilian labor would not be available due to the war, he conceived the idea of using prisoner-of-war labor for preparation of the model grounds. The Provost Marshal General, intrigued by the project, granted authority to construct an internment camp with facilities for 3,000 men adjacent to a model site.[27]

While Reybold tended to problems of labor supply and WES devised the model design, in October 1942 a site selection board that included Matthes, Tiffany, Caldwell, and Karl A. Dupes of WES recommended a location near Clinton, Mississippi, 35 miles east of Vicksburg and nine miles west of Jackson as a construction site. The 822-acre tract consisted of gently rolling land that would not require extensive excavation and had ready access to a rail line and electric power.[28] The following month, the Corps acquired the property and in January 1943 the Mobile District started construction. Plans provided for housing for WES personnel needed to direct model work in addition to facilities for prisoners. Occupation began in August 1943 with the arrival of about 200 prisoners, nearly all Germans from Rommel's elite Afrika Korps captured in North Africa. By October the number had risen to 1,400, then peaked at 1,797 in December.

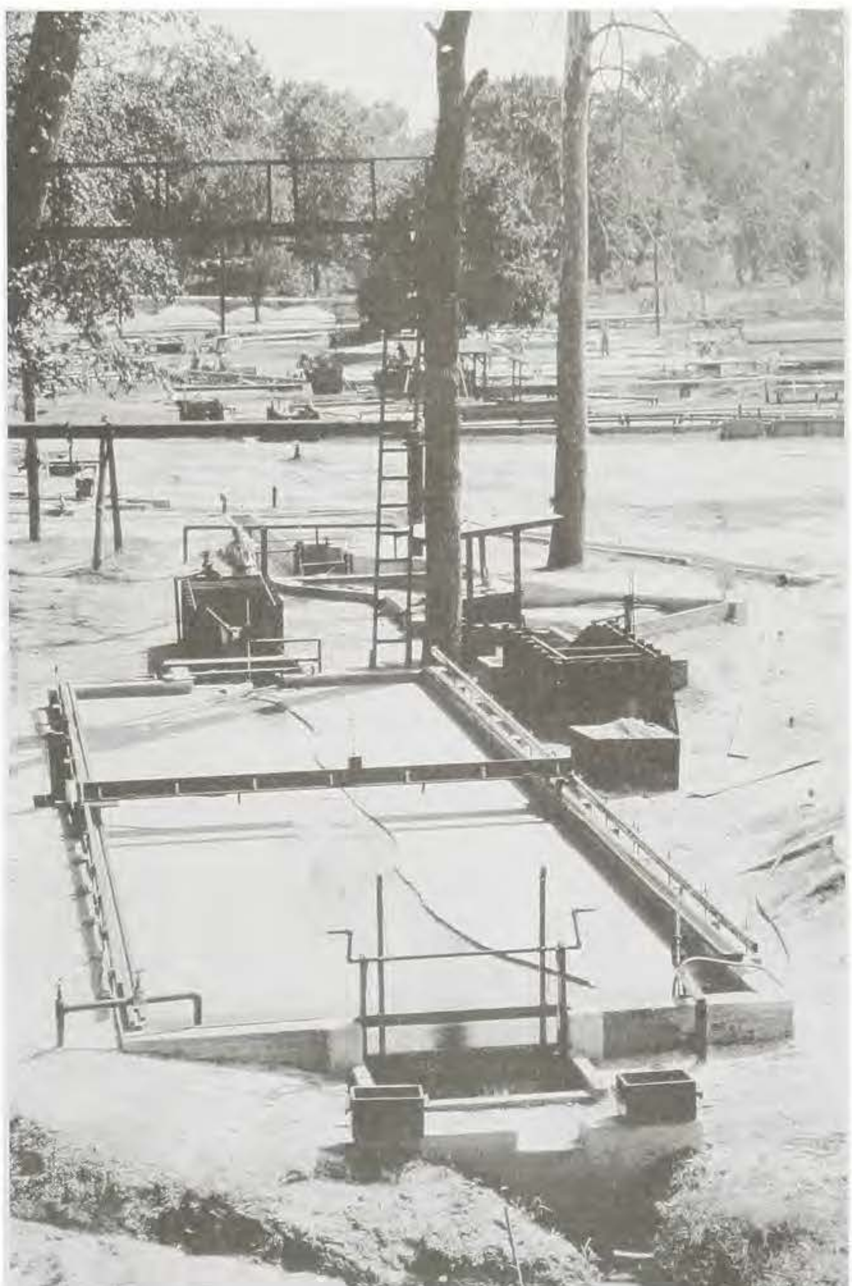
German prisoners of war doing site work on Mississippi Basin Model, Clinton, MS

Supervised by WES personnel, prisoners began work at the site immediately upon arrival. Enlisted men received 80 cents a day for eight hours of outdoor labor, with canteen scrip substituted for cash. Officers and noncommissioned officers were not required to work but could volunteer to do so. Workers showed a good deal of enthusiasm when first assigned to the project, but developed a real indifference when the majority of work changed to excavation with wheelbarrows and shovels. Morale improved after several months when heavy earth-moving equipment replaced the primitive tools used in early efforts. Eventually the prisoners cleared nearly 600 acres of land, built roads and bridges, moved a total of about 1,000,000 cubic yards of earth, dug a drainage ditch around the upper limits of the model, and installed most of a storm-sewer system with about 85,000 linear ft of pipe underlying the site. By the time the last prisoners were repatriated in May 1946 the location was nearly ready for construction of the giant model.[29]

Civil Projects: Meandering of Alluvial Rivers

While military research took precedence over civil works projects during the war years, WES continued to perform experiments. The Hydraulic Structures Section of the Hydrodynamics Division, for instance, completed studies of spillways and related dam structures at a number of locations, though on a reduced level from its prewar efforts.[30] Of enormous long-term significance, WES pioneered comprehensive theoretical studies of the meandering of alluvial rivers and supervised a revolutionary geological analysis of the Lower Mississippi Valley.

Meandering of the channel of the Mississippi and other alluvial rivers had long puzzled hydraulic engineers. As early as 1932 WES began a series of investigations for the MRC attempting to determine the distance over which the river would maintain its channel without meandering between consecutive curves. In simple tests, Station workers filled a 50-ft-long flume to a depth of about nine inches with sand, molded a straight channel down the center of the 15-ft-wide bed, and ran a constant discharge of water through the channel. Flows quickly developed meander belts in imitation of an alluvial river valley. Tests



WES directive energy flume

varied the slope of the valley, the rate of discharge of water, the amount of sand supplied with the water when it was introduced into the channel, and other factors. Lacking more sophisticated techniques and measuring devices, engineers concluded only that greater rates of bed load (sand in this case) supplied to the first bend in the model produced greater sized bends in a more rapid fashion. Efforts were discontinued when the MRC withdrew funding.[31]

Early directive energy study

In 1940 and 1941 WES performed a more complete set of experiments for the MRC for the purposes of "obtaining specific data on the natural tendencies of a model stream in regard to the development and maintaining of a definite meander pattern," and to "study methods of controlling and directing these natural tendencies." Near the completion of Ferguson's cutoff program, a coordinated levee system had led to revived MRC interest. Engineers were concerned that the Mississippi, despite straightening, would continue to change its channel negating the man-made cutoffs and bypassing expensive levees. Understanding meandering phenomena was seen as a key in shaping efforts to keep the river within a permanent channel, if possible. Use of crushed coal rather than sand as a bed material provided more realistic performance, as did use of small gravel and other materials on riverbanks to prevent unnatural scour and erosion. Efforts ceased abruptly in December 1941 when the engineers in charge were transferred to the Lower Mississippi Valley Division for military construction projects.[32]

Captain J. F. Friedkin conducted lengthy directive energy studies of meandering streams

Early efforts paled in relation to an MRC-sponsored program lasting from September 1942 to December 1944. Conducted first by Captain Haywood G. Dewey, Jr., then by Captain J.F. Friedkin, the study was to "determine the basic principles of meandering rivers," and "the principles involved as to the effects of stabilizing the banks of a meandering river." Tests used flumes up to 120 ft in length and 38 ft wide, with river channels up to 5 ft wide and 4 inches deep. A variety of bed materials were used, including coal, sands, silt, haydite, and mixtures. Time lapse photography using overhead cameras recorded water flows as they produced meanders, built up bars, scoured bends, created cutoffs, and in other ways imitated the behavior of a prototype river. In a constricted time scale, engineers could view in a matter of hours what would take decades to replicate in nature.

The study resulted in the publication of the seminal *Laboratory Study of the Meandering of Alluvial Rivers* by Friedkin in 1945.[33] Even before publication, Friedkin's work strongly influenced Congress in 1944 to authorize a comprehensive project of bank stabilization for the Mississippi River and creation of a 12-ft-deep permanent navigation channel. Profusely illustrated, the study became an instant classic distributed all over the world, although some conclusions have since been challenged or revised.[34]

Civil Projects: Geological Investigations

Geological investigations supervised by WES led to a reinterpretation of the fundamental nature of the Mississippi River Valley. By the late 1930s the Corps of Engineers recognized the interrelationship of geology with practically all forms of engineering. Thus, in the early 1940s the MRC sponsored a program of localized geological studies as part of its overall strategy to control flooding of the Mississippi River and its tributaries. These studies evolved into a compilation of the geological history of the entire alluvial valley of the Mississippi River and, eventually, its major tributaries. Concurrent with historical analyses, geologists amassed a comprehensive inventory of soil types, structures, and strata in the region and placed them in their geological context. Both historical and contemporary geological inventories proved invaluable, first to planners who were able to more fully understand the behavior of the river system and predict its future actions; and second to engineers who now had a inclusive view of the geological makeup of the valley, including information on the location of potential construction sites and materials.[35]

Fortunately, in the formative stages of its geological studies the MRC obtained the services of Harold N. Fisk, a young professor of geology at Louisiana State University.[36] In the late 1930s, Fisk combined lab and teaching responsibilities at LSU with a research position on the Louisiana Geological Survey, also headquartered in Baton Rouge. In the latter capacity he compiled and published a series of geological investigations that quickly drew the attention of a wider audience, including the Corps of Engineers.[37] Consequently the MRC engaged Fisk as a geological consultant, leading him to terminate employment with the Louisiana Geological Survey in 1941. Over the next few years he authored a series of unpublished reports for the MRC on a variety of topics ranging from geological studies of underseepage and sedimentation problems to investigations of proposed lock and levee sites.[38] These paled into relative insignificance with the publication of his monumental *Geological Investigation of the Alluvial Valley of the Lower Mississippi River* by the MRC in December 1944.[39]

"Fisk '44"

The origins of *Geological Investigation* — "Fisk '44" — dated to 1941 when OCE authorized a comprehensive geological study of the entire alluvial valley of the Lower Mississippi.[40] Detailed objectives included:

- a summary of the major characteristics of the valley,
- an analysis of the nature of the Mississippi entrenched valley system,
- an analysis of the nature and distribution of the recent geological era alluvium filling the entrenched valley system,

- a determination of the characteristics of the alluvial plain,
- a chronology and analysis of the historical evolution of the valley, and
- a comprehensive discussion of the Mississippi River and its activities.

Harold N. Fisk (far left), revolutionized geological studies of the Mississippi River Valley

No geological study of such magnitude had ever been attempted, nor one that could have such an enormous impact on hydraulic and geotechnical engineering in a major river system. Consequently OCE provided a wide range of resources, many furnished by WES. The project was nominally administered by Brigadier General Max C. Tyler, president of the MRC, but WES Director Matthes was de facto general supervisor. Prophetically, Matthes had been an early proponent of geological studies in engineering practice and was instrumental in establishing the discipline as an integral component of the Station's functions.[41] To conduct the investigation, Matthes established an independent WES Geological Division in Baton Rouge under the immediate direction of Fisk. There, a newly-hired staff afforded the needed personnel. Fisk then had at his disposal a professional WES contingent, resources from other Corps offices, and a mass of data accumulated by several state geological surveys, railroad corporations, state highway departments, water-well drilling companies, oil companies, and other entities.

From their Baton Rouge headquarters, WES personnel reviewed data and compiled preliminary reports. Only the developments of the previous 15 years made the project feasible. Prior to 1927 accurate maps were not available for much of the region, and water-well drillers, petroleum explorers, and construction engineers had made only scattered borings, few of sufficient depth. Seismic studies were likewise of little value. By the 1940s, however, Fisk and his associates had the advantage of a variety of new means. Topographic maps made by the MRC thoroughly detailed the surface of the alluvial plain, while aerial photographs provided a fresh perspective. The latter were most useful in identifying abandoned courses of the main river and its tributaries, where scars of old channels and associated features were discernible from the patterns of soils, vegetation, and drainage. Studies also utilized the data from approximately 16,000 borings, many made under the supervision of the WES group. Over 3,000 penetrated the entire depth of the alluvial layer. Historical accounts of the river valley were more thoroughly analyzed, some going back as far as Spanish narratives of the 16th century.[42]

In a concise 78 pages of text, the Fisk report addressed the objectives outlined in the research directive. Gaining immediate acceptance as a classic in geological investigations, for the next three decades it served as the authoritative and essentially unchallenged reference on the geological history of the alluvial region, and on the origin, location, nature, and thickness of alluvial sediments. Perhaps as impressive, several volumes of colored, detailed topographical and geological

maps and charts accompanied the manuscript. Prepared and published by the MRC, they set a new standard for geological illustration.

Even before the completion of Fisk's report in 1944, OCE authorized a major supplemental study published in 1947 as *Fine-Grained Alluvial Deposits and Their Effects on Mississippi River Activity*. In it geologists mapped the position of fine-grained alluvial deposits from aerial photographs and field examinations, testing the mapped areas through borings made specifically for the study. They also compiled information concerning the physical properties of different types of fine-grained deposits. Of particular importance, the 1947 study more accurately pinpointed and mapped abandoned channels, locating clays and other soils. This in many cases provided more practical information than the original study, as designers were better able to plan levees, revetments, and other structures in the future.[43]

The Valley Disclosed

The Fisk reports revolutionized perceptions of the Lower Mississippi Valley and had an enormous impact on virtually all engineering efforts therein. Among the report's conclusions was that the alluvial layer of the valley, the layer deposited by the Mississippi and lesser rivers throughout the history of the region, consisted of two thick, separate, and distinct strata. Concepts of "classical" geologists had previously held that the floodplain consisted of thin layers of alluvium. In fact, the two thick layers embodied a substratum of coarse-grained materials, primarily sand and gravel, laid during the earlier stages of the filling of the entrenched river valley. Above the substratum was a top stratum of fine-grained silts, clays, and silty-clays deposited during the later stages of river valley development. The substratum was often encountered at depths as shallow as 10 ft below the top stratum in the northern part of the valley and averaged 50 ft in thickness. In the southern part, from Baton Rouge to the Gulf, the substratum was as much as 100 ft below top stratum deposits with its thickness reaching 400 ft. The depth of the substratum beneath top stratum alluvium at any location was of crucial importance to engineers, as the substratum usually provided the stable foundation needed for major construction projects. Beneath the two strata of alluvial deposits, firm clay of Tertiary period origin constituted the foundation of the entrenched river valley.

Fisk's chronology of alluvial valley evolution also revolutionized standards in geological interpretation. He postulated that the foundation of the entrenched valley, the essentially solid base, was eroded during the last great Ice Age beginning about 30,000 years ago. Sea level was approximately 450 ft lower due to the incorporation of water into glacial masses. Thus gradients of the proto-Mississippi and other rivers in the region were steep, carrying potential alluvial deposits all the way to the Gulf of Mexico. The end of glaciation resulted in a rise in sea level to its present height only about 5,000 years ago. As the sea level rose, stream gradients steadily declined, river velocity decreased, and a great wave of alluvium spread upstream. Thus, according to Fisk, the alluvial plain was of relatively recent origin. Sand and gravel deposits — the substratum of the alluvial layer — fell first from flowing water, to be followed in deposition by the top stratum of finer-grained materials. This general interpretation of valley evolution remains popular and widely accepted, though later research indicates that Fisk seriously underestimated climatic and other factors. Major revisions of Fisk's chronology have also ensued.

Fisk reinforced conceptions that the establishment of a broad, easily eroded alluvial plain had led to the most salient characteristic of the modern Mississippi River: the active migration of its channel. Indeed, the term meandering well described its serpentine actions. Most meanders were pre-Columbian in origin and were thus unrecorded. A few European observers — primarily Spanish and French explorers — described changes in the river's course only as late as the 16th and 17th centuries. Eighteenth- and 19th-century accounts, especially those initiated by the MRC after the 1870s, provided a much more detailed record of river behavior in recent historical times.

To historical accounts, Fisk added the first comprehensive interpretation of the river's unrecorded past. Analysis of aerial photographs, topographical maps, and deep borings led Fisk to

deduce that within the past 2,000 years, a very short geological duration, the river had significantly changed its course several times. These alterations involved much more than the establishment of cutoffs and abandonment of localized channels, but rather sometimes incorporated entirely new main channels. Of particular importance, the river in its lowest reaches had taken at least three different routes through Louisiana to the Gulf of Mexico in the time span considered. The present course through New Orleans dated from only about the past 650 years. All observations and data indicated the river would continue to wander through the alluvial plain in the absence of human controls. Fisk's findings, supplemented by Friedkin's laboratory studies of river meandering, profoundly influenced Corps strategies to control the Mississippi, notably through construction of the massive Old River control complex in the 1950s and 1960s.

Aftermath of War

The surrender of Japan in August 1945 immediately reduced the military-related hydraulics functions of the Station, with civil works again taking center stage. Administrative and organizational evolution reflected the change in focus. Matthes retired as Station Director in September 1945 after a stressful 3-1/2 year tenure. His departure marked a fundamental change in the nature of the office. Matthes and his predecessors — Vogel, Falkner, Thompson, and Fields — were first and foremost hands-on engineers, all of whom could be considered pioneers in hydraulic modeling and played large roles in the Station's research activities. Future Directors tended to assume limited technical functions. Appointed by OCE, they were to administer and coordinate WES activities in performing Corps missions. Tenures normally lasted two or three years, as the Corps attempted to give its officers a broad range of administrative experiences by rotating them through important posts.

Before leaving WES, Matthes enacted a structural reorganization by merging Fenwick's Waterways Division and Brown's Hydrodynamics Division into a single Hydraulics Division. Fenwick became Chief with Brown as Assistant Chief. Matthes and his immediate successors, Lieutenant Colonel Clement P. Linder and Colonel Carroll T. Newton (a former Freeman Scholar), faced a touchy personnel problem in that returning veterans had the right to return to their old jobs or to assume positions to which they had been entitled at the time of their departure. Fortson had been Tiffany's successor as Hydraulics Division Chief when Tiffany became Assistant Station Director in 1941, but the Army transferred Fortson from WES. Shortly after his return to the Station in December 1945, Fortson replaced Fenwick as Hydraulics Division Chief, even though Fenwick had served in that capacity for the preceding three years. (This uncomfortable scenario repeated itself during the Korean War when Fortson again reported for active duty, left WES, was replaced by Fenwick, then returned to his old post.)

Transfer to OCE

The Station's duties expanded continuously during the war years and their immediate aftermath. Matthes, even before the end of World War II boasted that

> *The Waterways Experiment Station has become known as the largest and most active laboratory of its kind in the world. Although a great many other laboratories in this country and in foreign countries have done similar work in hydraulics and soil mechanics, no one of the laboratories approaches in number of projects nor in scope of problems the work carried on at the Experiment Station. As a matter of fact it is probably true that the Experiment Station has conducted as many hydraulic and soil mechanics investigations as all other laboratories combined.*[44]

WES traditional hydraulic model projects included studies for OCE, Corps divisions and districts, and other clients on a nationwide basis. The work included studies on flood control, harbor engineering, hydraulic structures design, and navigation improvement endeavors. Construction and operation of the Mississippi Basin Model alone dictated establishment of a separate section within the Hydraulics Division. Activities of the

Soil Mechanics Division grew to include airfield paving, mobility and trafficability studies, and engineering geology. The transfer of the Corps' Concrete Research Division from New York to Mississippi in 1946 further extended and diversified the Station's role.

While WES emerged as a leviathan in hydraulic engineering and soil mechanics, the Corps of Engineers made a conscious effort to centralize its research operations in those and other areas. OCE strongly encouraged districts to refer work whenever possible to WES. Even Corps laboratories considered permanent in the 1930s saw their functions absorbed by WES. The Station had clearly assumed a stature far beyond its original role of assisting the Mississippi River Commission in its flood control mission. By the late 1940s, only about one-fourth of WES hydraulics investigations were for the MRC and LMVD. Consequently, in August 1949 the Corps transferred administration of WES from the MRC to the Office of the Chief of Engineers. WES then exercised technical supervision over all hydraulic model tests for the Corps, whether performed at the Station, other Corps laboratories, or universities, and over any such soils, pavement, or concrete investigations directed to the Station by OCE. Further, the WES Director was to coordinate all civil testing programs, except testing of a routine nature normally performed in division laboratories, "to insure that the capabilities of the Corps of Engineers' civil works experimental facilities are effectively utilized."[45] Despite objections by the MRC — and at least two subsequent attempts by its presidents in the 1950s to return WES to MRC jurisdiction — the Station maintained a prestigious position within the Corps through its unimpeded relationship with OCE.

Notes

1. Tiffany, *History of WES*, V-4-5.

2. Ibid., 11.

3. Eloise Bodron, interview by author, Vicksburg, 8 September 1995.

4. Charles R. Warndof, "Military Projects of the Waterways Experiment Station," *The Military Engineer* 47 (1955): 342.

5. "Model Study of Locations for a Proposed Breakwater in San Juan Harbor, Puerto Rico," WES *Technical Memorandum No. 173-1* (Vicksburg: WES, 1940); and John E. Arnold, "Model Study of the Proposed Breakwater System for Roosevelt Roads Naval Base, Vieques, Puerto Rico," WES *Technical Memorandum No. 207-1* (Vicksburg: WES, 1944).

6. C.B. Patterson and John E. Arnold, "Model Study of the Pump Suction Chamber for Dry Dock No. 4, Puget Sound Navy Yard," WES *Technical Memorandum No. 189-1* (Vicksburg: WES, 1942).

7. R.A. Jackson and R.Y. Hudson, "Breakwater Location, U.S. Naval Air Station, Alameda, California," WES *Technical Memorandum No. 2-242* (Vicksburg: WES, 1947).

8. R.Y. Hudson, "Model Study of Wave and Surge Action, Naval Operating Base, Terminal Island, San Pedro, California," WES *Technical Memorandum No. 2-237* (Vicksburg: WES, 1947).

9. R.Y. Hudson, "Wave and Surge Action, Point Fermin Naval Supply Depot, San Pedro, California," WES *Technical Memorandum No. 2-238* (Vicksburg: WES, 1947).

10. "Wave and Surge Action, Long Beach Harbor, Long Beach, California," WES *Technical Memorandum No. 2-265* (Vicksburg: WES, 1949).

11. "Entrance Channel Currents, Naval Operating Base, Midway Islands," WES *Technical Memorandum No. 2-251* (Vicksburg: WES, 1948).

12. F.R. Brown, H.B. Simmons, and G.B. Fenwick, "Model Studies of Water Requirements and Salt-Water Intrusion, Intracoastal Waterway, New York Bay-Delaware River Section," WES *Technical Memorandum No. 221-1* (Vicksburg: WES, 1946).

13. "Model Study of Pontons and Pneumatic Floats," WES *Technical Memorandum No. 215-1* (Vicksburg: WES, 1945).

14. "Improvement of Freeboard Conditions on Pontons in High-Velocity Flow," WES *Technical Memorandum No. 2-256* (Vicksburg: WES, 1948).

15. Cotton, *History of WES*, 46-47.

16. WES produced a typewritten first interim report in October 1943. Other classified reports appeared in November 1943 and January 1944. "Model Study of Wave Action on Cellular Caisson Breakwaters," unnum. (Vicksburg: WES, 1943); and "Model Studies of Wave Action on Triangular and Cellular Caisson Breakwaters," unnum. (Vicksburg: WES, 1944).

17. Tiffany, 10.

18. Cotton, 47.

19. Pendergrass, 183-85.

20. William H. Smith, "Artificial Harbors for Normandy Beaches," *Civil Engineering* 15 (1945): 256.

21. Robert Y. Hudson, "Model Tests of Portable Breakwaters for D-Day Invasion Harbors," *Civil Engineering* 15 (1945): 408.

22. See Alfred M. Beck, Abe Bortz, Charles Lynch, Lida Mayo, and Ralph F. Weld, *United States Army in World War II. The Technical Services. The Corps of Engineers: The War Against Germany* (Washington: U.S. Government Printing Office, 1985), 293. Thompson later became an international editor for *Readers' Digest* magazine. An interesting personal view of the Normandy invasion is included in an luncheon address Thompson delivered to the AUSA in 1984, typewritten copy, WES Archives.

23. A overview of the Corps' role in the Rhine crossings is included in Barry W. Fowle, "The Rhine River Crossings," in Barry W. Fowle, ed., *Builders and Fighters: U.S. Army Engineers in World War II* (Fort Belvoir, Virginia: U.S. Army Corps of Engineers, 1992), 463-75.

24. Lieutenant Colonel Stanley W. Dziuban, "Rhine River Flood Prediction Service," *The Military Engineer* 37 (1945): 348-53; and "Flood Predictions by U.S. Engineers Complement Crossing of the Rhine," *Engineering News-Record* 37 (1945): 537.

25. Lieutenant Colonel Stanley W. Dziuban, "Hydraulics Model Experiments: Planning for Crossing the Rhine," *The Military Engineer* 38 (1946): 189-93. Seven of the dams were located in Switzerland and on the international boundary between Germany and Switzerland and were jointly controlled and operated by German and Swiss interests. German attempts to destroy or seize the dams would have had great

political as well as military repercussions. In a little-known operation, German troops in 1945 actually attempted to seize one of the dams but were repulsed by Swiss guards.

26. An excellent account of the construction of the Mississippi Basin Model is contained in Michael D. Robinson, "Rivers in Miniature: The Mississippi Basin Model," in Barry W. Fowle, ed., *Builders and Fighters: U.S. Army Engineers in World War II* (Fort Belvoir, Virginia: Office of History, United States Army Corps of Engineers, 1992), 277-94.

27. "Preliminary Report on Proposed Reservoir Operation Model, Mississippi River and Tributaries," WES *Mississippi Basin Model Report 1-1* (Vicksburg: WES, 1942); "Definite Project Report," WES *Mississippi Basin Model Report No. 1-3* (Vicksburg: WES, 1943); also J. E. Foster, "History and Description of the Mississippi Basin Model," WES *Mississippi Basin Model Report 1-6* (Vicksburg: WES, 1971).

28. "Report on Proposed Site," WES *Mississippi Basin Model Report 1-2* (Vicksburg: WES, 1942).

29. Robinson, "Rivers in Miniature," 284-86; also "History and Description of the Mississippi Basin Model."

30. For example, "Model Study of Spillway for Fort Gibson Dam, Grand River, Oklahoma," WES *Technical Memorandum No. 192-1* (Vicksburg: WES, 1943); "Model Study of Stilling Basin, Delaware Dam, Olentangy River, Ohio," WES *Technical Memorandum No. 205-1* (Vicksburg: WES, 1944); and "Model Study of Spillway, Allatoona Dam, Etowah River, Georgia," WES *Technical Memorandum No. 214-1* (Vicksburg: WES, 1944).

31. "Model Experiments to Determine the Directive Energy of a River," WES *Technical Memorandum No. 61-1* (Vicksburg: WES, 1935); "Effect of Sand Feed on Developments in Directive Energy Flume," WES *Technical Memorandum No. 61-2* (Vicksburg: WES, 1935); and "Consolidation and Grain Sorting in the Bed of the Directive Energy Flume," WES *Technical Memorandum No. 61-3* (Vicksburg: WES, 1935).

32. *Study of the Meandering of Model Streams. Preliminary Report of Progress to September 1, 1941* (Vicksburg: WES, 1941); also J.B. Tiffany, *Review of Research on Channel Stabilization of the Mississippi River, 1931-1962* (Vicksburg: WES, 1962), 18-32.

33. J.F. Friedkin, *A Laboratory Study of the Meandering of Alluvial Rivers* (Vicksburg: WES, 1945).

34. Tiffany, *Review of Research*, 33.

35. A brief overview of the importance of geological investigations in engineering practice is provided in Charles R. Kolb and Woodland G. Shockley, "Engineering Geology of the Mississippi Valley," *Transactions of the American Society of Civil Engineers* 124 (1959): 633-56.

36. Biographical information on Fisk is contained in "Memorials," *Bulletin of the American Association of Petroleum Geologists* 49 (1965): 209-12.

37. See, for example, Harold N. Fisk, "Geology of Grant and La Salle Parishes," *Louisiana Department of Conservation, Geological Bulletin 10* (1938); "Pleistocene Exposures in Western Florida Parishes," *Louisiana Department of Conservation, Geological Bulletin 12* (1938); "Depositional Terrace Slopes in Louisiana," *Journal of Geomorphology* 2 (1939): 181-200; and "Geology of Avoyelles and Rapides Parishes," *Louisiana Geological Survey Bulletin 18* (1940).

38. See, for example, Harold N. Fisk, "Geological Report on the Baton Rouge Underseepage Area," unpub. report for MRC (1942); "Geological Study of Sediments Adjacent to the American Cut-Off Revetment," unpub. report for MRC (1943); "Geological Investigation of Bayou Sorrel Lock Site Area," unpub. report for MRC (1946); and "Geological Investigation of Proposed Tensas-Cocodrie Levee Site," unpub. report for MRC (1946).

39. Harold N. Fisk, *Geological Investigation of the Alluvial Valley of the Lower Mississippi River* (Vicksburg: Mississippi River Commission, 1944). An excellent account of the investigative project and its conclusions is contained in Harold N. Fisk, "Mississippi River Valley Geology Relation to River Regime," *Transactions of the American Society of Civil Engineers* 117 (1952): 667-89.

40. The alluvial valley of the lower Mississippi is a broad lowland, varying in width from 25 to 125 miles, extending north and south for more than 600 miles from Cairo, Illinois, to the Gulf of Mexico. The channel of the Mississippi River in that expanse measures approximately 1,000 miles. The valley is characterized by alluviation — the long-term deposit of waterborne materials by the Mississippi and its tributaries — which has created the most distinctive geological characteristics of the region.

41. Particular insight into the establishment of the WES Geological Division and the role of Matthes in promoting geological studies is provided in Roger T. Saucier, interview by author, Vicksburg, 17 February 1993.

42. Ibid., 2-3.

43. Harold N. Fisk, *Fine-Grained Alluvial Deposits and Their Effect on Mississippi River Activity*, (Vicksburg: WES, 1947); also Roger T. Saucier interview.

44. Gerard Matthes, *Historical Summary of Work at the U.S. Waterways Experiment Station* (Vicksburg: WES, 1944), 9-10.

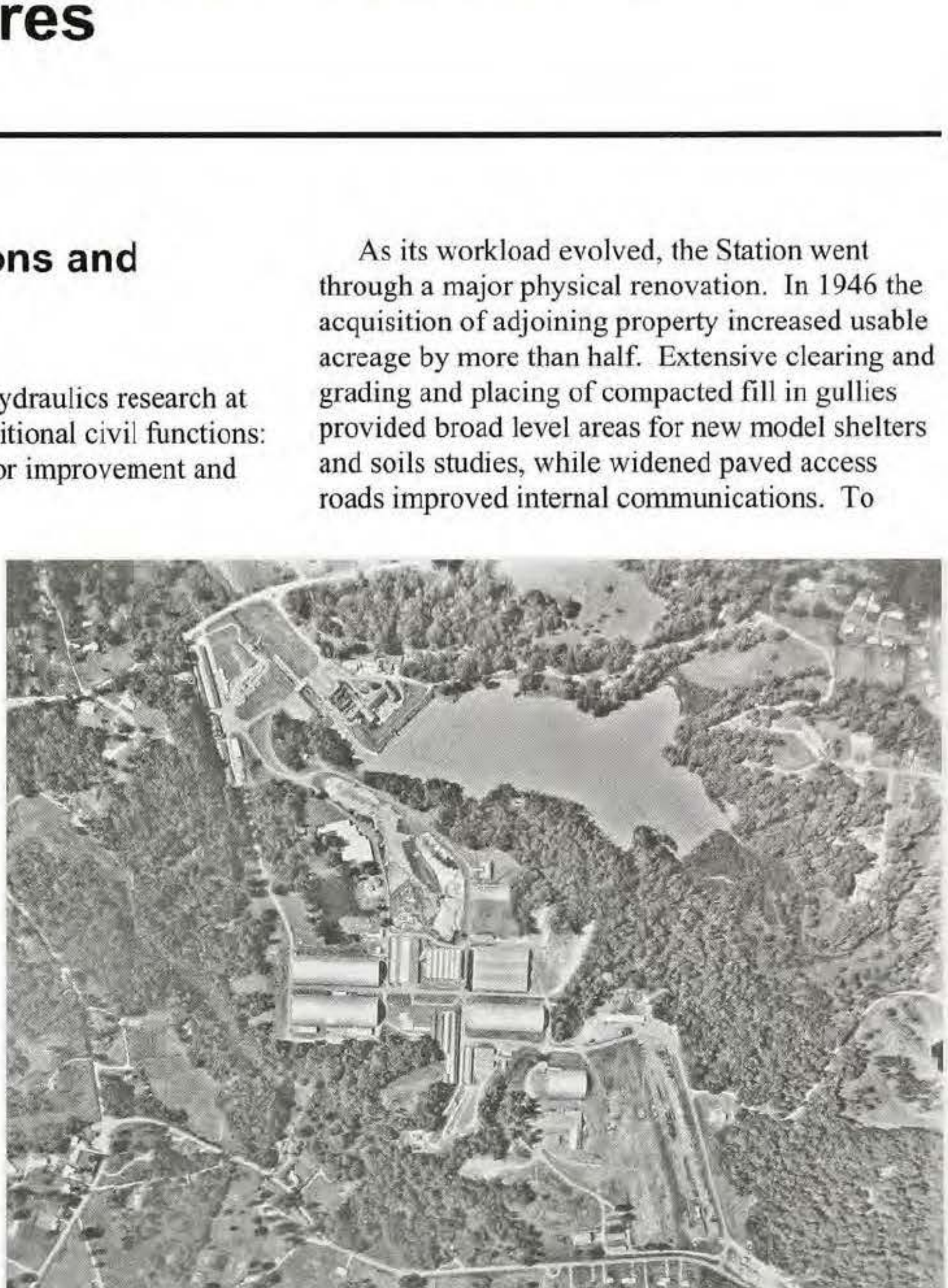
45. Vicksburg *Evening Post* 7 July 1949.

5 Hydraulics Research Giant, 1949-1963, Part I: River Modeling, Potamology, and Hydraulic Structures

Expanded Functions and Facilities

In the aftermath of war, hydraulics research at WES returned largely to traditional civil functions: flood control, river and harbor improvement and regulation, and design of hydraulic structures. Activities in these and other areas such as tidal estuary modeling and potamology increased far beyond prewar efforts. In addition, for the first time the Station assumed a program of applied research that, rather than concentrating on specific problems connected with individual projects or structures, appreciably broadened the scope of experimental work. Military endeavors, though greatly reduced, found an unexpected release in studies of the effects of nuclear explosions in water.

As its workload evolved, the Station went through a major physical renovation. In 1946 the acquisition of adjoining property increased usable acreage by more than half. Extensive clearing and grading and placing of compacted fill in gullies provided broad level areas for new model shelters and soils studies, while widened paved access roads improved internal communications. To



Aerial view of large metal hangars at WES to house models

serve Corps personnel in the Vicksburg area, where housing had been a critical problem in the prewar period, the MRC directed construction of a dozen single family homes, an apartment complex, and a small (and unpopular) trailer camp. Clearing underbrush from around the Station's lake improved its appearance, and grounds keepers waged a constant battle to clear the lake of turtles. One weekly "turtle report" to the Director listed a three-foot alligator among its victims. Snakes occasionally found models to be convenient resting spots.[1]

More importantly, new facilities replaced the outdated wooden sheds that housed numerous hydraulic models. Station Directors found that portable sheetmetal hangars, with materials obtained from military surplus, were both ideal and available. Through the late 1940s WES constructed a number of huge hangars on the graded upper level of the reservation adjacent to the Mississippi River Flood Control Model. By 1947 the center of activity for model studies had been moved from the lower level in front of the WES main building to new facilities on high ground. While the Hydraulics Division relocated most of its operations there, the Soils Laboratory occupied the central portion of the old main building, which had housed flumes, small models, and other hydrodynamic experimental equipment.

More Growing Pains

Growth inevitably altered relationships between WES employees. "Old hands" nostalgically recalled that the Station in its earlier years had benefitted from an extraordinary camaraderie. Its predominantly young cadre of engineers and technicians had been bound together by common experiences brought on by the Depression and World War II. Excited by the prospects of innovative scientific research, they maintained a level of interaction possible only in a limited, almost family-like atmosphere. Henry Simmons, a WES employee since early 1940, noted of the World War II era that "In those days everybody ate lunch together out on the lawn out of brown paper bags," and that there was constant discussion about what was going on. Everybody knew everybody else — including the director — by first name. Simmons also represented a generation of WES employees who found it possible to rise to prominence despite a lack of formal education. Later an internationally known pioneer in estuary modeling and WES Hydraulics Laboratory Chief, Simmons had dropped out of Mississippi State College for financial reasons halfway through his senior year. He never received a college degree.[2]


Henry B. Simmons

A listing of WES hydraulics projects in progress in 1950, the 20th anniversary of experimental work at the Station, illustrates the remarkable growth of the Hydraulics Division's activities during the previous decade. It also serves to indicate the difficulty of maintaining the close personal relationships that had benefitted the Station's personnel during its early years. With growth came distance.

From 23 projects in progress in 1940, the Division's workload had almost doubled to 42 in 1950. (A complete listing of projects in progress in 1950, with sponsors, is included in Appendix B.) Site-specific studies of dams and appurtenant structures included work for Belton Dam, Texas; Cheatham Dam, Tennessee; Folsom Dam, California; Fort Randall Dam, South Dakota; Garrison Dam, North Dakota; Genegantslet Reservoir, New York; Oahe Reservoir, South Dakota; and Philpott Dam, Virginia. River flood control and navigation efforts involved constructing and instrumenting the huge Mississippi Basin Model and model studies of Memphis Harbor, Tennessee; the Hoosic River, Massachusetts; and the Mississippi River near the Greenville, Mississippi, bridge. Another river project, begun for the Buffalo District, entailed model studies of the Niagara River and Niagara Falls necessary to design improvement and protective works. Large-scale models of Charleston Harbor, South Carolina; Delaware River Estuary; Grays Harbor, Washington; Raritan River Estuary, New Jersey; Savannah Harbor, Georgia; and Port Washington Harbor, Wisconsin, exemplified tidal and wave action research activities.

By 1950 OCE had for the first time also involved WES in a number of applied hydraulics research projects as a part of centralizing its research programs. Civil Works Investigations (CWI), unlike site-specific studies, involved broad research initiatives for general application. CWI projects in progress at the Station in 1950 represented a broad range of the Corps' hydraulics engineering mission, including: General Spillway Model Tests, Conduit Intake Model Tests, Cavitation Research, Sluice Outlet Model Tests, Model Study of Sluice Coaster Gate, Slide Gate Model Tests, Use of Air Instead of Water in Model Testing, Scale Effects on Spillway Discharge Coefficients, Hydraulic Capacity of Meandering Channels in Straight Floodways, Study of Wave Force on Breakwaters, Stability of Rubble-Mound Breakwaters, Study of Harbor Design, Scale Effects in Harbor Models, Analysis of Hydraulic Experimental Data, Effects of Model Distortion on Hydraulic Elements, Simulation of Air Entrainment in Models Involving High Velocity Flow, Hydraulic Instrumentation, Development of Turbulence Meter, Prototype Analysis, and Roughness Standards for Hydraulic Models.[3]

Administrative Evolution

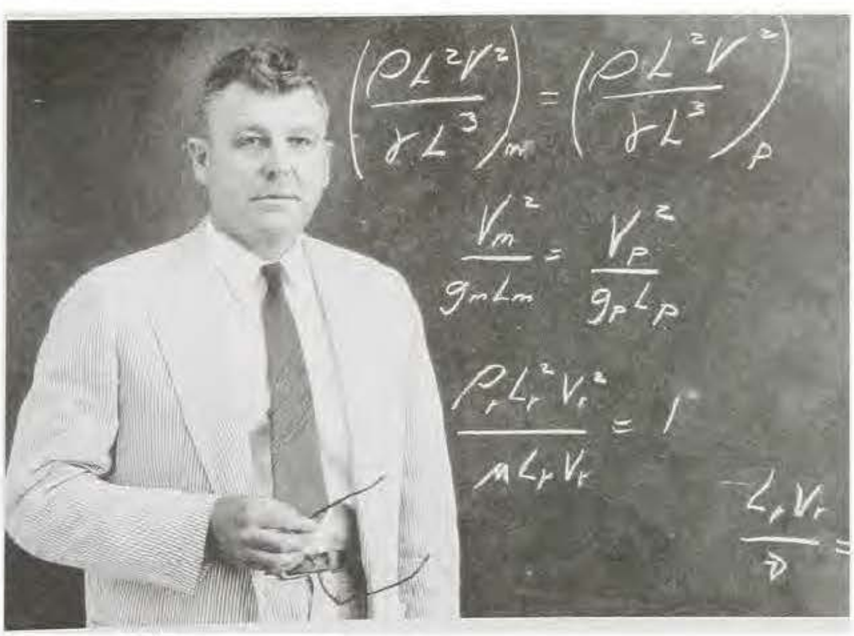
Despite its enlarged mission and the plethora of projects performed after World War II, for nearly two decades the administrative structure of the Hydraulics Division remained comparatively stable. Fortson served as Chief until 1970 with the exception of a stint in Korea from 1951 to 1952. From 1947 until 1951 the division consisted of only three branches:

Frank B. Campbell

- Hydrodynamics (Frederick R. Brown),
- Rivers and Harbors (George B. Fenwick), and
- Mississippi Basin Model (Haywood G. Dewey, Jr.; Henry C. McGee).

Thomas E. Murphy

In 1951 the Hydraulics Analysis Branch under Frank B. Campbell joined the existing three, but the following year the Rivers and Harbors Branch absorbed the Mississippi Basin Model Branch, restoring a three-branch structure. This arrangement lasted until 1962 with Fenwick, Brown, and Campbell continuing as chiefs. In that year Fortson added the Nuclear Weapons Effects Branch under Guy L. Arbuthnot, Jr. The Nuclear Weapons Effects Branch in turn left the Hydraulics Division in 1963 to become a separate division with Brown as Chief. The Hydraulics Division then expanded to five branches:



Eugene P. Fortson

- Estuaries (Henry B. Simmons),
- Hydraulic Analysis (Frank B. Campbell),
- Structures (Thomas E. Murphy),
- Water Waves (Robert Y. Hudson), and
- Waterways (John J. Franco).

This basic structure continued into the 1980s. (See Appendix A: Organization Charts.)

The Korean War

Peace in 1945 did not bring international stability. By 1948, as a reinvigorated WES faced its enlarged mission, the Grand Alliance between the Western democracies and Communist Russia had collapsed. The Soviet occupation of Eastern Europe and subsequent clumsy attempts to force the Western powers out of Berlin marked the onset of the Cold War. Within three years after the defeat of the Axis powers, the United States and the Soviet Union faced off as antagonists in a bipolar world. China's fall to communism in 1949 further intensified the confrontation between East and West.

The Cold War turned temporarily hot in June 1950 when Communist North Korea invaded South Korea. The United States responded immediately, sending regular Army troops to the Theater of Operations and calling up reserve units. One such reserve unit was the 434th Engineer Construction Battalion, established and sponsored by WES in 1948. Using WES facilities for training, the unit specialized in bridge and road building and repair. About seventy WES employees, many from the Hydraulics Division, reported for active duty in August 1950, then left for further training in Colorado before sailing for Korea in January 1951. Eventually over 100 Station personnel served with the 434th, while others joined different units. The drastic drop in manpower disrupted numerous WES functions, as did attendant sharp cuts in Federal expenditures for civil works.

George B. Fenwick

John J. Franco

Over 100 WES employees saw service in Korea with the 434th Engineer Battalion

Fortson, who had served with the 3rd Military Railway Service in Iran during World War II, commanded the 434th in the Theater of Operations from February through December 1951. As in the first conflict, Fenwick replaced Fortson as division chief until the latter's return in 1952. John J. Franco, another longtime Hydraulics Division employee, World War II veteran, and future Waterways Branch Chief, succeeded Fortson as battalion commander in Korea until June 1952. He was one of the last of the original troops to return to Vicksburg. The 434th performed with distinction in its wartime role, receiving a Meritorious Unit Commendation from Eighth Army Commander General James A. Van Fleet.

MBM: Administration and Construction

Construction and operation of the Mississippi Basin Model (MBM) more closely represented a return to the Station's original flood control mission than any other project of the immediate post-World War II era. To administer the "super-model," OCE in August 1945 established the Mississippi Basin Model Board to "determine policies and programs for the subsequent development and operation" of the giant facility. Members were the president of the MRC, the WES Director, the Missouri River, Ohio River, Southwestern, and Upper Mississippi Valley Division Engineers, and a representative of the Chief of Engineers. Functioning until 1970, the Board usually met on an annual basis, with sub-committees meeting more often during the interim. Subcommittees submitted numerous reports to the Board, which then produced detailed reports on its meetings and made recommendations pertaining to construction and use of the model.[4]

In 1946, within the WES administrative structure, Station Director Colonel Carroll T. Newton established a MBM Branch under Franco. The following year Dewey succeeded Franco. Dewey reported for active duty in August 1950, serving in Korea until late 1952. He then returned to WES and briefly assumed his former position as director before leaving the Station to head the Corps' model of San Francisco Bay in Sausalito, California. McGee guided the MBM Branch during Dewey's absence in Korea. On Dewey's permanent departure from WES, Fenwick's Rivers and Harbors Branch absorbed the MBM Branch, which was reduced to section status.

One of the Station's most notable hires assigned to the MBM was Margaret S. Petersen. Shortly after graduating from the University of Iowa in civil engineering, Petersen and her best friend and fellow Iowa graduate Irene Miller responded positively to job offers from Tiffany. (The pair had gotten a total of two job offers – one from WES, the other from the library of a paper company in Wisconsin.) Although they "didn't have the faintest idea where Vicksburg was," and "couldn't find it on the maps," the two arrived at WES in August 1947. From August 1947 until November 1949 Petersen reviewed and analyzed hydraulic, topographic, and hydrographic data for designs of proposed testing programs and model-operating techniques. She also was in charge of several research projects while teaching courses in fluid mechanics for the WES staff. On the latter date Petersen became one of the first and only female administrators in the Corps, rising to the office of Chief, Research Sub-Section, Mississippi Basin Model Operation Section, WES.[5]

Margaret S. Petersen

In 1952 Petersen and Miller applied for leaves of absence without pay to pursue graduate studies at Iowa. However, many of the Hydraulics Lab's employees were expected to return from the Korean War in the near future and assume their prewar positions. Because there was not a lot of work available and funding was insecure, the WES personnel office refused to grant a leave of absence to Petersen and Miller. Both resigned from the Station in order to return to school. Petersen went on to a stellar career with the Corps, including a short stint back at WES in 1964 during which she served at Chief, Wave Dynamics Division, Water Waves Branch, Hydraulics

Laboratory. After retiring from the Corps in 1977 she served as an associate professor in the Department of Civil Engineering and Engineering Mechanics at the University of Arizona. Her *River Engineering*, published in 1986 became a standard work in the field. In 1995, looking back on her years at WES, Petersen opined that her experiences at the Station had been invaluable due largely to the wide variety of hydraulic engineering work in progress and, more so, to the "very competent" Hydraulics Lab employees and consultants that served as role models.[6]

After prisoners of war prepared most of the model site by 1946, WES crews directed by Dewey began construction of the concrete portion of the model proper. The original WES Definite Project Report, submitted to OCE in April 1943, predicted model completion about one year after site preparation. This overly optimistic calculation may well have been based on previous WES experiences, such as construction of the Mississippi River Flood Control Model in 1935. In that instance WES had built the giant edifice — then the world's largest hydraulic model — in a mere four months.

MBM construction, in fact, continued at a varying pace until 1966. The long building process was due primarily to irregular funding and, less so, to unforseen technical problems. Funding went through an unusual and often disruptive sequence. WES in the beginning charged construction, operation, and maintenance costs to the divisions having sections to be reproduced in the model. The divisions in turn prorated costs to their districts through complicated formulas. By the mid-1950s this method had become so unreliable that Congress took over funding. Beginning in Fiscal Year 1957 direct Congressional appropriations covered construction and verification of the model. Amounts ranged from a low of $400,000 in that year to $810,000 in Fiscal Year 1958.

The sheer size of the MBM presented new construction demands. Covering an extensive area, over 200 acres, it had to be built in sections

Map of area reproduced by Mississippi Basin Model and drainage basin of Mississippi River

with expansion joints between them to absorb the expansion and contraction of the concrete. Areas between concrete sections were sodded to prevent erosion. Until 1953 workers constructed individual section blocks directly in place on a carefully prepared subgrade using the traditional template method. This involved cutting sheetmetal templates to cross sections obtained from topographic maps and set about 2 ft apart to the correct elevation on the model site in positions located by a rectangular grid system. Crews then placed concrete between the templates and molded it to correct elevations. Highly expansive clay beneath the model caused undue shifting and by 1953 WES engineers developed a contour method for completion of the rest of the model. Using enlarged contour maps for construction plans of sections to be molded, technicians fabricated the sections on an assembly line. Section blocks then cured for seven days before being carried by truck to the model site and set on concrete piles. The piles extended to a depth of 10 feet, passing through the


Mississippi Basin Model construction


Completed Mississippi Basin Model

expansive clay stratum to where the soil moisture content was stable. Although slower and more expensive, this provided the necessary equilibrium.

Reproduction of model details also consumed substantially more time than previous efforts. The MBM eventually included all bridges, levees, highway and railroad fills, and other pertinent elements of the extensive prototype. Corps districts furnished information so Federal and many private levees could be modeled to location with proper heights, grades, and alignments, while highway departments and railroad companies provided data necessary to simulate their construction efforts. Channel and overbank roughness required further refinement. WES engineers working with a pilot model determined that carefully brushed and scored concrete, concrete ridges, and concrete and brass parallelepipeds (usually cubes), properly spaced, could accurately simulate channel roughness. To replicate overbank phenomena such as trees, workers installed folded screen wire cut to the scale of the average height of trees where aerial photographs showed trees in the prototype. Expanded metal fastened to the model on cleared areas provided adequate resistance to flow where the brushed concrete was not effective, with some areas requiring two or three metal layers.

MBM Instrumentation

MBM designers from the earliest stages of its development considered automatic instrumentation desirable and necessary. Total manual operation of the model would require a full-time staff of about 600, which would be unduly expensive and difficult to train and maintain. Available manually controlled instruments also could not accurately reproduce and chart some complex Mississippi Basin phenomena. WES devoted approximately four years, from 1943 to 1947, to the study of automatic instrumentation and to the testing of commercial and pilot instruments embodying various design principles. After investigating products of about 125 manufacturers throughout the United States, model engineers determined that available instruments did not have the accuracy of measurement or the range required for use on the model. Consequently, WES developed specifications for new instruments and invited manufacturing companies to bid or to submit designs for alternatives that would accomplish the desired results. In 1948 contracts awarded to Infilco, Inc., Chicago, and Leupold and Stevens Instruments, Portland, led to production of the necessary automatic devices.[7]

The MBM incorporated three types of automatic instruments: inflow, stage, and outflow. A single master timing device synchronized the operations of all. Centrally located instrument houses on the major streams provided control centers. Programmers located in the control houses could regulate the introduction of water into the model through the inflow controllers, monitor water levels with stage devices, and measure discharges at selected points on a stream with outflow instruments. Automatic recorders, also in the

Mississippi Basin Model instrumentation

control houses, made permanent records of data received electrically through transmitters, in addition to registering the month, day, and hour of model flood periods as determined by the master timer.[8]


Mississippi Basin Model automated control center

WES engineers continued to make improvements in instrumentation while the model was being constructed. Use of automatic instruments was a complete success. Hundreds of tests indicated that automated experiments were typically more accurate than manually conducted ones, especially when identical tests were repeated. Rather than the 600 personnel needed to manually run the MBM as originally projected, the new instruments required only 60. Savings were about 50 percent, as the cost of the instruments in use on the model was offset by the savings in salaries required for manual operation.[9]

The 1952 Flood

Piecemeal construction of the MBM had certain benefits. Partly at the insistence of Station Director Linder, WES sectionalized the model so various parts could be used for separate studies without involving the entire facility. Portions of rivers such as the Missouri, Tennessee, or Arkansas could be tested independently as they were completed to study local problems. Thus the model was "many models in one." As individual sections were completed, engineers installed instruments, added roughness and other features, and verified them for local testing. Verification usually involved reproduction of the maximum flood of record for each reach of the model. After introduction of model equivalents of the flows for that flood, crews adjusted channel and overbank roughness to make model stages agree with those of the prototype. With the model thus adjusted to reproduce past occurrences, it was expected to produce occurrences that might be experienced in the future. Construction and verification generally proceeded geographically from north to south, since the Mississippi Flood Control Model at the Station already covered most of the river reach below Memphis.[10]

MBM directors put some individual sections into operation as early as 1949. Fortuitously, by 1952 the Missouri River segment was fully operational. In April of that year a great flood threatened to reach a crest discharge of almost twice the maximum flood of record at Sioux City, Iowa. The Missouri River Division (MRD) requested WES to operate the MBM on a 24-hours-a-day basis to assist in predicting crest stages and discharges. During a critical 16-day period, WES and MRD personnel maintained almost constant contact by telephone. Model tests first indicated that levees at Council Bluffs and Omaha were not high enough to contain the crest of the flood. The MRD subsequently evacuated the affected areas and raised the levees five days after the WES prediction. Flood crests exceeded the original grades of the levees but were contained by the recent additions, saving the two cities from flooding. Further tests indicated that certain levees should be raised but that others would be overtopped before efforts would be effective. The MRD then concentrated on building up levees where there was a chance to prevent overtopping and evacuating people from other locations. This spectacular use of the model, according to the MRD, was a prominent factor in the success of the flood fight that prevented damages of an estimated $65 million.[11]

Basin-Wide Testing Program

By 1959 the model had been completed downriver as far as Memphis. MBM directors then began a comprehensive testing program that coordinated the entire model structure as it expanded. Further construction by 1966 added the Mississippi River from Memphis to Baton Rouge, the Arkansas River, and the Atchafalaya River basin. Basin-wide tests, which continued through 1969, concentrated on analyzing the effectiveness of reservoirs in controlling floods and in developing procedures to obtain the greatest overall flood protection. Further tests were to determine the efficiency of Corps plans for operation of floodways and to check the adequacy of project levees in the Lower Mississippi River Valley.[12]

The lengthy test series reproduced four historic floods, 1937, 1943, 1945, and 1952, for which adequate data were available. Each had different characteristics and represented various ways in which floods occurred on the Lower Mississippi. The 1937 flood, for example, was the maximum flood of record on the Ohio River and portions of the Lower Mississippi, while the 1943 and 1945 events saw flooding of the Missouri River as well as the Ohio and Mississippi. Tests also reproduced three hypothetical floods representing early spring, late spring, and winter phenomena. Procedures involved introducing model equivalents of the flood flows at 114 model inflow points on the major tributaries and routing flows through the model to the downstream end at Baton Rouge or through the Atchafalaya Basin. All seven of the model floods were reproduced six times, each time with a different set of variables, most of which pertained to operation of existing or planned reservoirs.

Mississippi Basin Model visitors

MBM Sightseeing Facilities

During its period of basin-wide testing the MBM gained international renown as a tourist attraction. Beginning in 1964 visitor facilities provided self-guided tours on a seven-day-a-week basis. Facilities included a visitor assembly center, a 40-foot-high observation tower, an operation observation room near the center of the model, and elevated platforms, walks, and sidewalks at selected locations throughout the area. Maps, pictures, other visual aids, and recorded lectures provided visitors with information about the model and other work done by WES and the Corps of Engineers. Through the remainder of the decade the model drew about 5,000 visitors a year, including domestic and foreign engineers, Corps officials, and sightseers in general. Perhaps more than any single construction project completed by the Corps of Engineers — and certainly by WES — the MBM brought public attention to the development and possibilities of hydraulic modeling.

MBM Retired

With its basin-wide testing program completed in 1969, the MBM no longer had a clear mission. Tests on individual problems continued into 1971, but high operating costs and declining demand for conventional model studies, largely due to the use of computers to replace or complement model investigations, led Corps leaders to put the MBM on a standby basis.

The Corps found one more use for the mighty model in 1973. In the fall of 1972 heavy rains in the Mississippi River basin saturated the ground and filled flood control reservoirs. By the following April the Lower Mississippi River experienced its largest flood in decades. A potentially disastrous situation arose at the Old River control complex when a wing wall failed and a large scour hole developed in front of the structure. Failure of the entire structure would have resulted in the Mississippi taking a new main channel down the Atchafalaya basin, bypassing Baton Rouge and New Orleans.[13] MRC President Major General Charles C. Noble considered opening the Morganza Floodway, which had been completed just downriver from the Old River complex in 1953. However, the floodway had never been operated and serious questions arose concerning the impact of its use on the Atchafalaya basin and whether it would divert polluted water through Baton Rouge and New Orleans. Noble consequently requested reactivation of part of the MBM for tests. Despite having only two remaining full-time staff, the MBM was operational within 48 hours. Tests performed on an around-the-clock basis over a three-week period indicated that opening the Morganza Floodway would improve conditions at the Old River complex without endangering water supplies at Baton Rouge or New Orleans. Also, the veteran model again showed the ability to pinpoint levees that were in danger of overtopping.[14] (The emergence of numerical modeling and the expense of maintaining the MBM, led the Corps to finally relinquish control over the facility. In 1993, the city of Jackson took custody of the MBM.)

Mississippi Basin Model revived during 1973 Mississippi River flood

Niagara Falls and St. Lawrence Seaway Projects

With the major exceptions of the MBM and the Mississippi River Flood Control Model, WES activities involving river models declined precipitously in the years following World War II. This indicated the Corps' shifting priorities from flood control, which had progressed geometrically since the early 1930s, to other engineering areas. Two notable WES projects used river models in attempts to preserve and enhance the beauty of Niagara Falls and to facilitate construction of the St. Lawrence Seaway. Rather than flood control, both centered on aesthetic, industrial, and navigational factors, and both were fraught with political as well as technical difficulties.

Since 1877 both the United States and Canada had diverted water from the Niagara River above Niagara Falls to produce electric power. Treaties in 1909 and 1910 limited diversions to daily quotas for each country to preserve the scenic beauty of the falls. In order to meet wartime power needs during World War II, a further series of agreements increased diversions. Fearful that continuing diversions would diminish the attractiveness of the falls, yet highly dependent on diversions for power, the United States and Canada in 1950 signed a comprehensive new treaty to regulate use of the Niagara River. Although power requirements were an important consideration, the treaty specified that the primary obligation of the two governments was to "preserve and enhance the scenic beauty of the Niagara Falls and River," and stated that the two countries would complete any remedial works necessary to distribute water so as to produce an unbroken crest line around the falls for all flows.[15]

Administration of the treaty fell to an International Joint Commission, which in turn established the International Niagara Falls Engineering Board. The Board, drawn from technical agencies of the two countries involved, was to undertake an engineering investigation of the Niagara River and Falls and to make recommendations to the parent organization. The Buffalo District and the Federal Power Commission furnished experts for the United States. In addition to beginning onsite investigations in 1950, the Board called for model studies. Since the project was international and inherently sensitive, both countries constructed models, ostensibly to complement one another. Sponsored by the Buffalo District, in late 1950, Fenwick, Earnest B. Lipscomb, Robert G. Cox, and Cody D. McKellar of the Rivers and Harbors Branch began design and construction of a model at WES. At the same time, the Hydro-Electric Power Commission of Ontario built a second model at Islington, Ontario, although substantially smaller and with different scales than its WES counterpart.[16]

Reproduction of the prototype area involved a set of problems not encountered in earlier river models. Unusually swift currents, eddies, the dramatic drop in elevation from Lake Erie to the stretch below the falls, the large volume of water cascading over the falls, and the presence of water intakes for power plants were alien to more traditional studies. In addition, the lack of hard data concerning channel depths, current speeds, and other phenomena that the model had to incorporate forced project field engineers to invent new investigative methods. These included suspending weights on steel cables from helicopters in order to determine water depths and tracing current directions by studying aerial photographs of ice flows. Model verification further required uncommon adjustments for roughness — added with wire screening, stucco, sheet metal, and small rocks — to reproduce turbulence in the vicinity of the falls.[17]

Upon completion and verification, the indoor WES model covered an area nearly the size of a football field, representing part of Lake Erie, 26 miles of the Niagara River, Horseshoe and American Falls, and the scenic stretch approximately one mile below the falls. Even bridges and the proposed and existing power intakes were precisely incorporated. In 1951 a first test series determined that increased water diversions for power, as allowed by the 1950 treaty, would result in "intolerable" effects on the falls if no remedial works were constructed. This led to evaluation of several proposed plans of remediation. WES tests indicated that the key element in maintaining adequate flows would be a 1,705-ft-long gated control structure built into the river from the

Canadian shore above the falls. Based on these model studies, in 1953 the International Joint Commission adopted a scheme calling for construction of the control structure, but reduced its length to 1,550 feet. However, the structure was to be designed so additions could be made if needed. Other hydraulic adjustments included extensive excavations and fills on both flanks of Horseshoe Falls. Model tests also showed that a proposed 450-foot-long gated structure near the U.S. shore was not necessary.[18]

By 1957 the International Commission had supervised construction of the massive control structure. Although results were generally quite good, flow levels at the falls were at times somewhat less than anticipated. Proposed design revisions for power intakes above the falls were also a source of some concern. Consequently, in 1959 WES conducted a follow-up study to evaluate the effectiveness of the prototype gated control structure. Tests reinforced the WES recommendation that the edifice extend 1,705 feet into the channel rather than the 1,550 feet originally accepted by the commission.[19] Upon completion, the addition allowed adequate flow diversions for hydroelectric power while maintaining the falls as one of the great scenic wonders of the world.

Construction of the St. Lawrence Seaway, another joint effort by the U.S. and Canadian governments, benefitted from WES model studies.[20] Plagued by controversy and opposed by various commercial elements such as railroads and East Coast ports, technical planning for the massive project began in 1940. In that year the Corps of Engineers established the St. Lawrence River District solely to carry out survey work and to submit plans for features to be included in the vital International Rapids Section. A 46-mile-long stretch forming part of the border between New York State and Ontario Province presented by far the most challenging engineering and political problems. In 1942 the St. Lawrence River District submitted an extensive design memorandum for the river reach that the Corps accepted as the basis

The Niagara Falls model, unlike most river models designed for specific studies, remains active over 40 years after its construction. However, its operation is no longer concerned with the prototype and has no direct technical value. It served in the 1990s as a highlight for visitors on the official WES tour, still illustrating in spectacular fashion the evolution and value of hydraulic modeling.


Barnhart Island -- Lake St. Francis Reach, St. Lawrence Seaway model

for any subsequent action. OCE then dissolved the St. Lawrence River District and delegated its responsibilities to the New York District.[21]

Both American and Canadian engineers concluded that model studies would be necessary to determine optimum designs in several areas. In the Galop Rapids Reach, a notoriously treacherous stretch near the head of the International Rapids Section, the St. Lawrence District had actually submitted two designs that differed substantially. Both involved extensive excavation of a navigation channel, relief cuts, addition of structures to reduce river velocities, and removal of various existing structures such as dikes and locks. The New York District asked for model studies to test the effectiveness of both plans, a project that OCE assigned to WES in early 1943. In June of that year Fenwick spent two weeks at the St. Lawrence site conferring with project experts and studying surface currents. He discovered several discrepancies between Corps drawings and actual prototype behavior and also noted that river maps did not show


South Cornwall Channel, St. Lawrence Seaway indoor navigation model

numerous eddies and other local flow characteristics. In a relatively rare occurrence, human experience and observation substituted for technical expertise: Fenwick and the New York District Engineer relied heavily on a local commercial fisherman, Ed LaFlair, to furnish details concerning the river bottom and surface flow patterns. At Fenwick's insistence, LaFlair spent several weeks at the Station as a consultant.[22]

On his return to WES, Fenwick supervised construction of a fixed-bed model of the Galop Rapids Reach with Shields E. Clark, Jr., as project engineer. Part of the model consisted of removable and interchangeable concrete blocks so different river conditions and alterations could be tested without breaking and remolding sections of the model. Changes were so extensive that the concrete blocks were soon abandoned in favor of a soil-cement mixture soft enough to be carved to desired configurations but hard enough to resist erosion or deformation. Early results of the two-year testing series, completed in October 1945, indicated that the first St. Lawrence District design was unworkable because it would not effectively reduce river velocities. The District's alternate plan also had serious deficiencies. WES studies then went far beyond their original intent of testing the two proposals, resulting in numerous changes. This led to the Corps' acceptance of a WES-developed revised alternate plan ultimately implemented by the St. Lawrence Seaway Development Corporation in the Galop area.[23]

Lipscomb supervised further St. Lawrence tests from 1955 to 1958, requested by the Buffalo District while the Seaway was under construction. A 1956 series involved reproduction of a 4-mile section of the Long Sault Canal, including the massive Eisenhower Lock and Grass River Lock, to determine the effects of surges in the canal between locks.[24] Other investigations used two models of the highly complex Cornwall Island Reach near the lower end of the International Rapids Section. A small, detailed model dealt only with cross-currents between Barnhart Island and Cornwall Island, while its larger outdoor counterpart miniaturized several river miles above and below Cornwall Island. Tests in both utilized a remote controlled replica of a large ore-carrier-type ship such as those used on the Great Lakes. As a result of WES efforts, the Corps recommended adjustments to the river channel that would divert more water to and require more dredging on the Canadian side of Cornwall Island.[25] In one of the most controversial issues of the entire Seaway project, the Canadians rejected U.S. recommendations, largely for political reasons. The Corps eventually accepted the Canadian position, a decision that led to substantial difficulties in implementation.[26]

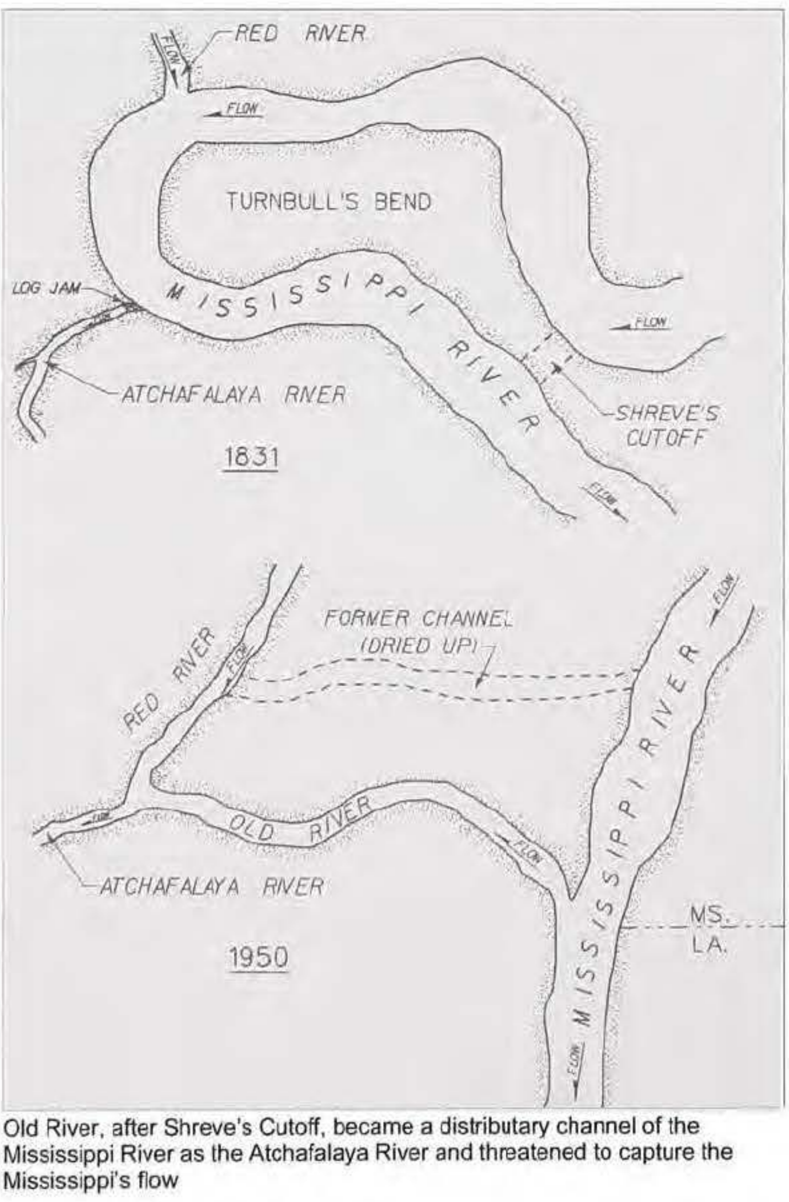
The Old River Dilemma

While the MBM took shape and Niagara Falls studies were completed, WES hydraulics engineers and geologists became acutely concerned with conditions that could potentially alter the entire regimen of the Lower Mississippi River. Harold N. Fisk's geological reports on the Lower Mississippi River Valley, conducted under WES auspices in the 1940s (discussed in Chapter 4), brought intensified attention to an old problem. In the early 1800s the Mississippi River channel followed a large meander to the west near Angola, Louisiana, called Turnbull's Bend. It was located about 300 river miles from the mouth of the Mississippi at Head of Passes and 80 miles upriver from Baton Rouge. The Red River flowed as a tributary into the Mississippi channel at the upper west end of the bend.[27] At the lower west end of the bend the upper end of the Atchafalaya River trickled into the Mississippi. The Atchafalaya channel stretched lazily south to the Gulf of Mexico near Morgan City, Louisiana. During high water periods the Mississippi reversed the flow of the upper Atchafalaya, turning the smaller stream into a distributary.[28]

In 1831, Shreve ordered a channel dug across the narrow neck of Turnbull's Bend, eliminating the meander. The Mississippi immediately took the new shortcut and the upper channel of the bend dried up. However, the lower channel of the bend, which connected to the Atchafalaya, continued to flow. This vestigial link became known as Old River. By the late 1800s water from the Mississippi flowed more regularly through the Old River channel into the Atchafalaya, even at normal river stages, eventually converting the smaller stream into a permanent distributary.[29]

The MRC expressed strong concerns about the Mississippi-Atchafalaya connection in the late 1880s. Even earlier, some river observers had speculated that the Atchafalaya might eventually capture the main channel of the Mississippi.[30] Flow of the Mississippi into the Atchafalaya continued to increase into the 20th century. In 1932 one of the first WES hydraulics reports warned of the inherent danger of diversion.[31] Still, it was Fisk's 1944 report that brought the problem into focus. For the first time, Fisk interpreted Mississippi River diversions in detail based on geological studies of floodplain features. He concluded that major changes in the river's channel had occurred when an actively meandering loop of the Mississippi, such as Turnbull's Bend, reached an adjacent flood basin, such as that of the Atchafalaya, and intersected a tributary stream that had a channel capable of carrying low-stage flow from the big river. Fisk's data also indicated that, historically, the flow of the Mississippi had gradually shifted from an existing main channel to such a new course over a span of no more than 100 years. A critical period seemed to be reached when a distributary captured about 40 percent of the Mississippi's flow, after which diversion was inevitable. Thus if geological analyses of previous diversions were accurate, the Atchafalaya was an ideal prospect for a new main stream in the relatively near future.

Old River Geological Investigations



Old River, after Shreve's Cutoff, became a distributary channel of the Mississippi River as the Atchafalaya River and threatened to capture the Mississippi's flow

By the mid-1940s the MRC, the Corps, and others had reached the point of alarm. Readings indicated that discharge from the Mississippi into the Atchafalaya was swelling at a disturbing rate. In the meantime, WES geological operations had moved from their original base in Baton Rouge to the Station, where in 1948 Station administrators established a Geology Branch as part of the Soils Division. Most of Fisk's WES contingent in Baton Rouge then relocated to the Station.[32]

With Fisk as a consultant, WES conducted more detailed investigations of the Old River phenomenon that confirmed that diversion was highly probable.[33] Pessimistic projections indicated that if diversion continued at the prevailing rate, the major part of the flow of the Mississippi would be captured by the Atchafalaya by 1968. More conservative opinions held that the main river would not change course until about 1985. Corps leaders accepted 1975 as a reasonable compromise. Sentiment was unanimous that a major change in the river's course would spell drastic ecological alterations and economic disaster.

Old River Model Studies

Action was imperative. Corps leaders began to consider several proposals for dealing with the threat of river diversion. Ultimately they opted for a complex arrangement of edifices involving an Old River closure dam, a new inflow channel into Old River with a navigation lock, an upriver low-sill control structure and channel into the Red-Atchafalaya system, and a lengthy overbank control structure for use during flooding. Never had engineers attempted such a project to manage the channel of a major alluvial river. The low-sill structure was of utmost importance, as it would regulate flow of the Mississippi into the Atchafalaya basin even at low water periods. It also presented the most challenging technical problems.

In 1947 the MRC commissioned WES model investigations to determine the effects of the proposed control structures on stages and flow conditions in the Mississippi River, the Red River, and the Atchafalaya River and basin. Tests employed the venerable Mississippi River Flood Control Model under the supervision of Lipscomb, assisted by Joseph W. McGee of the Rivers and Harbors Branch. Model reproductions of three floods, the 1927 and 1945 prototypes and the synthetic project flood, provided data. These indicated that the control complex would effectively prevent river diversion and also enabled the Corps to plan coordinated use of the complex during floods with the Morganza Floodway, only three miles downstream.[34]

In 1953, in a more specific study, Fenwick and Franco supervised construction and operation of a smaller model that replicated only the 11 mile river reach in the immediate vicinity of Old River. Experiments concentrated on determining the effects of the proposed control complex on sedimentation in the Mississippi River and on the flow from the Mississippi into the Atchafalaya River. As a result of the study, the Corps enacted a major revision in its plans, reversing the relative positions of the overbank control structure and the low-sill structure. Whereas the original construction proposal placed the low-sill structure upriver from the overbank control structure, model tests showed that this would produce undesirable sedimentation phenomena.[35]

Portion of Mississippi River Flood Control model showing Old River control structures

Further Geological Investigations

While hydraulics specialists analyzed the riverine aspects of the Old River project, construction engineers recognized that before any major edifices could be designed in detail, further geological evaluations of the entire Old River area were necessary. The massive facilities — especially the low-sill structure — required foundations built on complex subsurface strata. Excavations at the low-sill site would extend approximately 65 feet below the surface of the ground. Consequently, engineers insisted that foundation conditions at each construction site be adequate to assure that settling of the structures would be uniform and not excessive. Also, the new intake channel and lock channel demanded the location of erosion-resistant materials to support them.

In 1949 the MRC, in one of its final acts as administrative agency of WES, authorized a major Old River geological investigative project. Station personnel took more deep borings in the area, scrutinized aerial photos, and addressed a thorough review of geological composition and chronology.[36] A second WES investigation, ordered by OCE and completed in 1953, involved further borings and provided an inclusive subsurface review.[37] Fisk, who left LSU in 1950 for a position with Humble Oil, served as consultant on both studies. The WES reports led to the selection of the most advantageous locations for erection of the control complex in terms of soil and strata composition.

Old River Hydraulic Structures

After the Corps accepted the control complex plan and specific site selection, Brown's Hydraulics Structures Branch performed a series of studies aimed at evaluation and design improvement of a number of Old River mechanical elements. Experiments involved replication of such components as the vertical-lift gates of the low-sill structure, panel-gates of the overbank structure, and filling and emptying systems of the Old River Lock.[38]

While the Corps refined plans for the Old River project, implementation of the plans would require Congressional and Executive approval and a massive appropriation of funds. The Eisenhower administration looked skeptically at any large water project. The Old River problem involved a particular sense of urgency; thus, Congress in 1954 approved with the support of the Administration the Corps' entire Old River design plan and authorized $47 million to start construction. Work began on the low-sill structure in late 1955. Further appropriations followed, allowing completion of the project by 1965. The complex stands as one of the world's great engineering feats, although damages resulting from the 1973 flood caused grave concerns.

Potamology Investigations

Concurrent with construction of the Mississippi Basin Model and design of the Old River Control Complex, WES engineers began the most extensive investigations ever conducted of the fundamental nature of the Mississippi River. These were, to a degree, an enlargement and continuation of WES directive energy, bed materials, and sedimentation studies in the 1930s and of Friedkin's experiments on the meandering of alluvial rivers during World War II. Encompassing all aspects of the river's constitution and behavior, this potamology or river science program involved personnel of both the Station's Hydraulics and Soils Divisions in addition to outside consultants.

Failure stimulated the potamology program. By the 1940s the Corps had spent tens of millions of dollars in attempts to stabilize the channel of the Mississippi. The greatest single expenditure was on revetments — covering the river's banks with materials to prevent cave-ins, scour, or other changes caused by the action of water on the soil. Revetments commonly covered not only the above-water banks, but extended substantial distances underwater along the river bottom into the channel. Since the late 19th century, revetments on the Mississippi had evolved from the use of crude interwoven willow mattresses, held in place by rocks, to articulated concrete slabs fastened together with steel cables. River


Early interwoven willow mattress revetments

engineers faced a constant battle in keeping revetments in place, as failures were common and expensive.

By the 1940s the revetment program took on added importance. Since the Corps' overall plan for flood control in the Lower Mississippi Valley called for massive new levees, many of which were under construction, it was necessary to keep the river's channel between levee lines. Continued meandering would threaten the levee system and necessitate costly setbacks. To compound the problem, the straightening of the river channel by the Corps' cutoff program had increased current velocities, accelerating bank caving and meandering.

Events of 1946 were particularly distressing. During the low water season of that year the Vicksburg District placed new revetments on the actively caving bank of Reid-Bedford Bend, about five miles downriver from Vicksburg. That fall a major failure removed several hundred thousand cubic yards of bank material and several hundred feet of the new revetment in a matter of hours. Further massive failures at the site in late January and early February 1947 duly alarmed Corps planners. Shortly thereafter the MRC commissioned WES to perform a major study of river meandering and bank stability. Station Director Colonel John R. Hardin then called a conference of WES, MRC, and Vicksburg District engineers with the grandiloquently stated purpose of "Finding out Why Mississippi River Revetments Fail so Rapidly and What Can Be Done About It." Hardin expressed his obvious chagrin by stating that "The condition of the river today indicates that no ground whatever is being gained."[39]

Within a matter of months WES proposed a program of study accepted by the MRC. Objectives included:

- a study of the meandering tendencies of the Mississippi River with the view toward development of a model which could be used to predict future changes within a specific river reach,
- a revetment investigation to determine the nature of revetment failures and methods to prevent such failures,
- a study of methods of channel stabilization by means other than use of revetments, and
- development of comprehensive plans for the improvement of specific troublesome reaches of the Mississippi River.

The Hydraulics Division was to conduct several large-scale laboratory projects and coordinate activities of the Soils Division, its Geology Branch, and the Instrumentation Branch. The Memphis, Vicksburg, and New Orleans Districts were to provide personnel and equipment for field observations.[40]

In April 1948 WES hosted the first of a series of potamology conferences. Hardin encouraged representatives of the MRC, WES, and the three districts involved to give intensive thought to means for determining bank and revetments failures and developing methods of preventing them. Later that year a second conference included outside hydraulics consultants for the first time. Boris A. Bakhmeteff of Columbia University and Lorenz G. Straub of the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota provided expertise on certain river phenomena, especially the influence of turbulence. Hunter Rouse of Iowa University joined Bakhmeteff and Straub the following year, giving WES invaluable ties to the most advanced academic institutions engaged in hydraulic research in the United States.[41] Since soils studies were an integral part of the potamology investigation, soil mechanics pioneers Arthur Casagrande of Harvard University and Donald W. Taylor of MIT also participated in future conferences, either in conjunction with the hydraulics consultants or in some cases only with WES soils specialists.[42]

Potamology Field Investigations

Both the Hydraulics and Soils Divisions conducted field investigations. Largely due to the influence of Bakhmeteff, efforts of the former concentrated on measurement of river turbulence and on attempts to determine the effects of turbulence on underwater revetments. Almost no empirical data existed for turbulence phenomena. Early attempts in 1948 and 1949 were unsuccessful, largely because adequate instruments were not available. Project directors determined that experimental equipment must be designed that could accurately measure turbulence in deep, swift

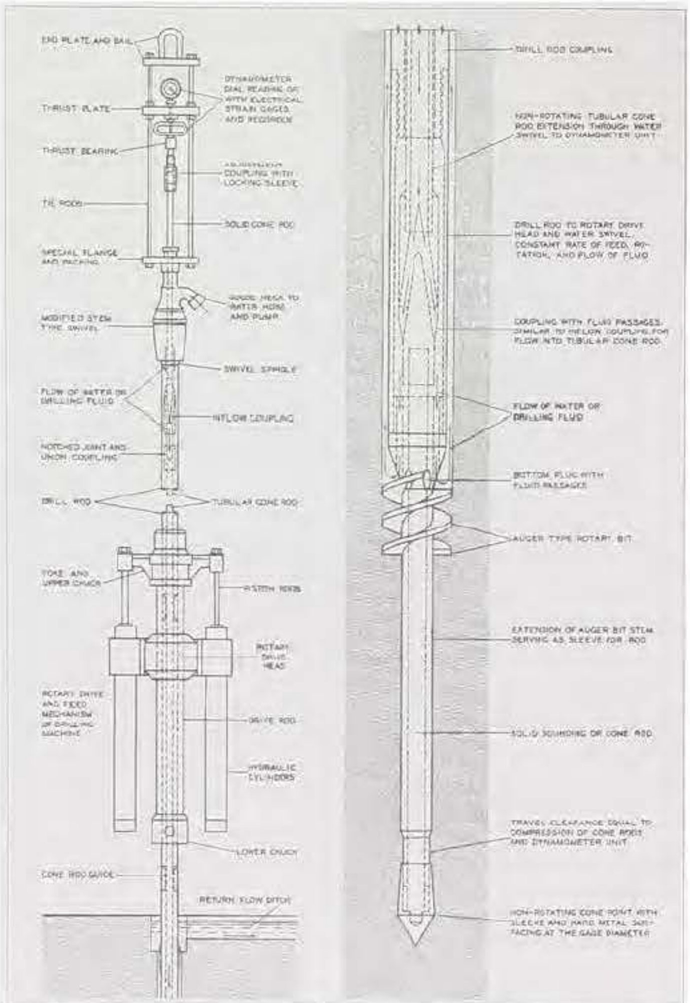
Hydrodynamic pulsimeter

WES potamology conference (from left): M. Juul Hvorslev, Stanley J. Johnson, Joseph B. Tiffany, George B. Fenwick, Lorenz G. Straub, Eugene P. Fortson, Boris A. Bakhmeteff, John J. Franco, Eugene H. Woodman (1949)

water while suspended at any desired location from a boat or barge. By 1950, WES engineers had developed a hydrodynamic pulsimeter that met the desired requirements. The full-scale instrument consisted of a 2,700-pound cast-iron disk, 5 feet in diameter and 4 inches thick, that could be suspended from cables. A rudder along with horizontal and vertical stabilizers provided equilibrium in even very swift currents and kept the device in proper orientation with water flow. In the center of the disk a pressure cell measured pressure fluctuations, while a current meter attached to and suspended immediately above the disk measured velocity fluctuations. An oscillograph recorded all data.[43]

Use of the apparatus in 1950 enabled field crews to obtain accurate measurements of pressure and velocity variations in the Mississippi River for the first time. Computations made by Bakhmeteff, reinforced by field measurements, indicated that slabs of concrete revetment even as thick as 6 inches or greater could be lifted from the bottom of the river by turbulent forces. However, before more data could be obtained, wartime funding cuts resulted in suspension of most hydraulic investigations in the potamology program.[44]

Soils studies were more lengthy. In a first-phase project, directors specified particular areas for investigation, where revetment had failed or where bank slides had otherwise been troublesome. These included such obscure river reaches such as Point Menoir, Hardscrabble Bend, and Wilkinson Point. The last provided a spectacular, though distressing opportunity for analysis in 1950 when more than 4 million cubic yards of bank slid into the river, destroying and completely removing a considerable length of revetment. The slide extended far enough laterally into the bank to crevasse the main-line levee 800 feet inland, starting overbank flooding behind the levee line. Only an emergency construction effort by the New Orleans District averted a catastrophe. At all locations soils personnel first collected and reviewed existing data, including geological



Rotary cone penetrometer designed by Hvorslev

M. Juul Hvorslev

studies and existing borings. An extensive boring program, further geological analyses, and other tests produced detailed reports on soil types, subsurface strata, permeability, and other factors likely involved in bank failures.[45]

Accepted soil mechanics theories held that riverbank slides, including those under revetments, could result from three different types of failures: shear failure; failure by scour; or flow failure. Shear failure occurred when the forces acting on a soil exceeded the strength of the soil. Failure by scour followed when a sufficient quantity of sand was scoured by river action at the toe of a bank of revetment to permit the top stratum to slide into the river. In what WES engineers and consultants considered the most likely scenario, flow failure occurred as a result of the sand substratum of a bank becoming saturated with water, decreasing the shearing resistance of the sand and leading to instability of the slope. Observations and a process of elimination led the potamology team to conclude that the failures under consideration resulted from flow failure, especially the liquefaction of fine sands in point bar deposits.[46]

Soils studies also led to improved instrumentation and soils sampling methods, prescribed goals of the potamology program. Advances were largely the responsibility of M. Juul Hvorslev, a native of Denmark whom WES hired as a special technical consultant in 1946. In potamology investigations, field crews found locating and sampling of fine-grained sands, materials especially susceptible to liquefaction, to be very time consuming, expensive, and sometimes impossible with existing equipment and methods. Under Hvorslev's guidance, WES designers developed a rotary cone penetrometer that, when attached to a truck-mounted drilling assembly, had the capacity to measure strengths of fine sands at depths up to 200 feet. Extensive lab tests, correlated with field experiences, proved its relative accuracy.[47]

In 1954 potamology investigators initiated a second-phase soils study aimed at locating sites where revetments were planned susceptible to flow slides. Each year WES personnel performed penetrometer tests and borings and evaluated all borings from revetment sites made by the

Memphis and Vicksburg Districts. By 1962 WES had compiled reports on 78 revetment sites. Of 30 locations where flow failures had occurred, WES studies predicted that 24 were unstable. Of the remaining six, five occurred at boring locations for which no prediction could be made due to lack of data. One failure took place near a location predicted to be stable, but the failure was more than 800 feet from the nearest boring and the boring data may not have been representative of soil conditions at the failure site.[48]

Potamology Laboratory Investigations

Laboratory investigations performed at the Station first concentrated on channel stabilization by means other than revetment. Model studies using dikes and baffles indicated that such structures could provide substantial protection to riverbanks in some circumstances.[49] Efforts to provide alternatives to conventional concrete-slab revetment, such as the use of sand-asphalt revetment, were disappointing.[50] Further attempts were aimed at developing a movable-bed model and operating techniques that could be used to predict future changes within a specified reach of the Mississippi River. Project directors elected to reproduce the Concordia-Scrubgrass Bend reach because it had experienced considerable bank recession and channel changes, but was not complicated by any man-made structures such as revetments or dikes. Lack of a material in the model that could both simulate the varying cohesiveness of prototype caving banks and serve as a true bed-load material after caving into the stream posed a particular problem. After numerous trials, engineers developed a crushed bituminous coal for use in the model bed, but mixed a binding agent with it to simulate cohesive properties of the river's banks. Although the model appeared to reproduce conditions in the prototype, as called for in the original potamology investigational plan, the Corps did not call for further specific studies.[51]

Tests supervised by Straub at the University of Minnesota produced controversial results. Using a full-size concrete revetment mattress in a large flume, researchers attempted to reproduce turbulence in the Mississippi River that might lift or depress underwater revetment blocks. Since none of the revetment blocks were ever lifted off the bottom in model tests, project personnel concluded that turbulence was not the cause of such phenomena in the prototype. This conflicted with turbulence theories advanced by Bakhmeteff and Rouse and furthered by Tiffany that appeared to be supported by empirical evidence. Tiffany, in fact, completely discounted the Minnesota revetment tests.[52]

Hydraulic Structures Development

Continuing its traditional function of evaluating designs for hydraulic structures, Brown's Hydrodynamics Branch performed a lengthy succession of investigations through the late 1940s and 1950s. In some areas these for the first time involved WES directly in a program of applied research. Whereas the Hydraulics Division had previously been concerned, at least officially, only with problems connected with the design of individual structures or with plans for specific flood control or navigation projects, WES engineers had long seen the need for a broader experimental program. Coincidentally, proposals for the establishment of a WES applied research program originated simultaneously at OCE and at the Station in February 1947, with letters from both offices proposing such a program passing each other in the mail. As a result of that correspondence, OCE designated WES as its primary research facility in a number of CWIs. The first were entitled "Wave Force on Breakwaters," "Stability of Rubble-Mound Breakwaters," "Study of Harbor Design," "Scale Effects on Harbor Models," and "Cavitation." By 1949 OCE had assigned further CWI projects to the Station including "Effect of Model Distortion on Hydraulic Elements," "Roughness Standards for Hydraulic Models," and "Opening Forces on Miter-Type Lock Gates." Work on lock gates, although authorized in 1949, did not begin until 1958.

WES hydraulics consultants conference, 1948 (from left): R. L. King, Eugene H. Woodman, Robert T. Knapp, Robert Y. Hudson, Hunter Rouse, Thomas E. Murphy, Arthur T. Ippen, Eugene P. Fortson, Frederick R. Brown

OCE guidelines for its CWI programs allowed WES to contract outside consultants on a continuing basis. The Station quickly moved to establish ties with the most renowned hydraulics experts literally from coast to coast. In November 1948 the Hydraulics Division hosted its first conference for consultants, with Robert T. Knapp of the California Institute of Technology, Morrough P. O'Brien of the University of California at Berkeley, Arthur T. Ippen of MIT, and Rouse of the University of Iowa attending. The consultants familiarized themselves with the Station's facilities and staff, then discussed directions, designs, and techniques they felt WES research should take.[53] Bakhmeteff and Straub joined Rouse and O'Brian as consultants for the first two WES conferences on cavitation and model distortion.[54]

Breakwater Design

Early WES CWI projects concentrated on breakwater design. As structures employed to reflect and/or dissipate the energy of water waves, thus preventing or reducing wave action in an protected area, breakwaters had been in common use since early Roman times. Breakwaters for navigation purposes are constructed to create sufficiently calm waters in a harbor area, thereby providing protection for the safe mooring, operating, and handling of ships and protection of shipping facilities. Sometimes breakwaters are constructed within large, established harbors to protect shipping and small craft in an area that would be exposed to excessive wave action. Offshore breakwaters serve as aids to navigation or shore protection or both, and differ from other breakwaters in that they are generally parallel to and not connected with the shore. By the mid-20th

century, the Corps of Engineers was responsible for over 600 breakwaters of various sizes and designs.[55]


Generalized harbor breakwater model

Rubble-mound breakwaters are the largest and most substantial of various breakwater types and are used almost exclusively in offshore and major coastal harbor protection schemes. They are typically constructed with a core of quarry-run stone, sand, or slag, and protected from wave action by one or more stone underlayers and a cover layer composed of stone or specially shaped concrete armor units. The structures are suitable for nearly all types of foundations and any economically acceptable water depth. They can be designed for either nonbreaking or breaking waves, depending upon positioning of the breakwater and the severity of anticipated wave action during the economic life of the structure.

Small-scale tests of rubble-mound breakwaters had been in progress at the Station since 1942, mainly for the Navy's Bureau of Yards and Docks. These first determined whether the breakwater proposed for construction at Roosevelt Roads, Puerto Rico, would be adequate to withstand the attack of the largest waves occurring at the site. Shortly after the model investigation began, the Roosevelt Roads project declined in military importance and tests on the original problem were discontinued. However, because of the lack of knowledge concerning the phenomena of waves attacking rubble mounds, the Bureau of Yards and Docks authorized WES to broaden the scope of the investigation to include a study of problems of a general nature. Directed by Hudson and Jackson, the test sequence continued intermittently until 1950.[56]

Early investigations led to two important advances: development of model designs, appurtenances, and techniques necessary for further research; and an appraisal of the accuracy of existing formulas for design of rubble breakwaters. For tests, WES designed a large concrete indoor flume 18 ft wide, 5 ft deep, and 119 ft long, with the depth representing water 58 ft deep in a prototype. It could be partitioned longitudinally by the insertion of a dividing wall, creating narrower test lanes. A mechanical generator produced waves of desired heights and characteristics, ranging up to prototype waves 21 feet high by 300 feet long. These were measured by electrical gages designed specifically for that purpose, while an oscillograph recorded gage data. The wave and measuring mechanisms were used not only for the Roosevelt Roads breakwater project, but for other investigations such as the study of wave and surge action at the Terminal Island Naval Operating Base at San Pedro Bay, California.[57] The size of the flume made possible the hand construction of model breakwaters of various compositions, materials, designs, and slopes which could be subjected to a wide variety of wave attacks.


Large flume for breakwater tests

Using the flume and its appurtenances for a broadened scope of investigations in addition to site-specific studies, WES researchers evaluated breakwater design formulas already in use. Data appeared to indicate that one formula, first published by Ramon Iribarren Cavanilles in 1938, was sufficiently accurate for design of rubble breakwaters, but only if used in conjunction with coefficients developed during model tests. An alternative Epstein-Tyrrell formula was found to be of no greater accuracy.[58]

Succeeding the early test program for the Bureau of Yards and Docks, in 1951 Hudson's Wave Action Section of the Hydrodynamics Branch began a long-term CWI program intended to integrate all important variables affecting the stability of rubble-mound breakwaters. More intensive investigations indicated that the Iribarren formula was less reliable than had been previously thought. WES then discontinued its use in correlating test data and Hudson developed a new, but similar, formula derived both from theory and from the results of model tests.[59] This formula was eventually adopted by the Corps of Engineers and has been used worldwide.[60]

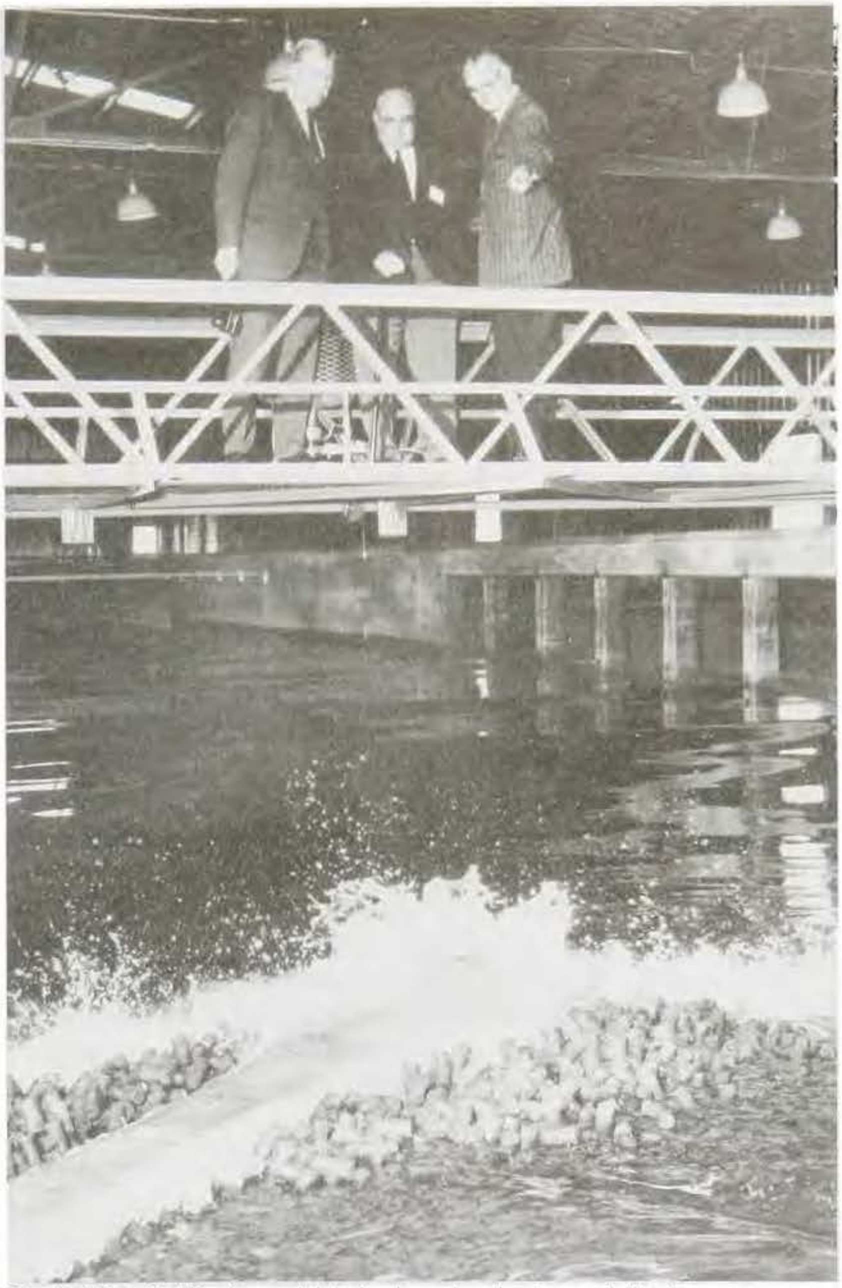
A number of general and site-specific investigations in the late 1950s and early 1960s dealt with recently-developed alternatives to conventional stone or concrete slab breakwater armor layers. Use of molded tetrapods, tetrahedrons, modified cubes, tribars, hexapods, and other special shapes, for instance, could be beneficial where adequate stone resources were not available or the molded shapes could be more damage resistant. Tetrapods, the first in the new generation of armor units, were developed at Danel's *Laboratoire Dauphinois d'Hydraulique* at Grenoble in 1950. Extolling their merits, Danel claimed that tetrapods were much superior to either concrete blocks or quarried stone and could reduce construction costs in some cases by as much as thirty percent.[61]

In 1953, at the behest of the South Pacific Division, WES conducted a study that for the first time involved evaluation of tetrapods for use by the Corps. Although the program was site-specific, it fell under the Corps' CWI initiative for general research, as the distinction between specific studies and their potential for broader application had always been blurred. Substantial damage had occurred to the breakwater at Crescent City Harbor, California, caused by storm waves and by waves that overtopped the breakwater even in normal circumstances. Because quarried rock of sufficient size to insure stability of the breakwater was not available locally, the Division Engineer requested tests of tetrapods as an alternative. WES efforts aimed at determining the size tetrapod required to insure the stability of the breakwater for different slopes and design-wave heights, and the optimum number of tetrapod layers that a protective cover would need. Conclusions were that 35 ton tetrapod units would be sufficient, if slight damage could be tolerated, and that two tetrapod layers provided optimum stability.[62]

Despite this endorsement of tetrapods and encouraging results in subsequent CWI tests,[63] by the early 1960s a number of other designs produced superior results. Water Waves Section tests in 1958 indicated that tribars, an armor unit developed by Robert Q. Palmer of the Corps' Honolulu District, were more economical than tetrapods.[64] Quadripods, another American design, were also shown to perform as well as tetrapods.[65] Further efforts in the late 1960s and 1970s dealt largely with dolos armor units developed in 1966 by E.M. Merrifield and J.A. Zwamborn.

The Corps of Engineers incorporated WES research in breakwater design, including use of both quarrystone and manufactured armor covers, in its authoritative *Engineer Manual 1110-2-2904, Engineering and Design: Design of Breakwaters and Jetties* in 1963. It and individual WES publications influenced breakwater design on an international level. Within the continental United States, construction or repair projects at Harbor of Refuge, Barcelona, New York; Port Washington, Wisconsin; Burns Harbor, Indiana; Monterey Harbor, California, and many other locations relied on WES recommendations.[66] Further afield, WES site-specific studies guided efforts at Nassau Harbor, Bahamas; Tsoying Harbor, Taiwan; and at Nawiliwili Harbor, Lahaina Harbor, Kahului Harbor, and Hilo Harbor, Hawaii.[67]

Hydraulic Design Criteria


Humbolt Bay, California, model during large breakwater model tests

WES solidified its position as the Corps' clearinghouse for hydraulics-related information through the establishment of a Hydraulic Analysis Branch in 1951. OCE transferred Frank B. Campbell from the Omaha District to head the new organization, which was responsible for the digest of thousands of technical papers, reports, graduate theses, and other publications and the dissemination of up-to-date design criteria.[68] In 1952 the branch published the first edition of *Hydraulic Design Criteria*, a looseleaf design manual for ready use by field engineers. The addition of new materials as data became available kept the original version updated on a continuous basis. Concentrating on spillway, outlet work, and gate and valve design, the first issue consisted of only 11 charts and five explanatory sheets, with 250 copies distributed. By the mid-1960s this had expanded to over 230 charts and 140 pages of text, and circulation surpassed 2,500 copies per year. Of that number, over 500 were distributed within the Corps, while other Federal agencies, consultants, universities, private individuals, and engineering firms on a national and international level purchased the remainder.[69]

Lock Design

As in breakwater and hydraulic structure design, WES involvement in lock design began with site-specific studies before evolving into a general research program. A first WES modeling effort, directed by Brown and Thomas E. Murphy in 1946 and 1947, dealt with the filling characteristics of Algiers Lock, Louisiana. In the New Orleans District, the lock was to connect the Mississippi River and the Intracoastal Waterway.[70] Murphy was yet another Depression-era engineer who had first been hired in 1935 as a temporary gage reader.[71] Further WES studies in the 1950s analyzed filling and emptying characteristics of the Calumet River Lock, Illinois, and the Barge Canal Lock on the Sacramento River in California.[72] A project from 1960 to 1962 furnished filling and emptying design specifications for Holt Lock and Dam on the Warrior River in Alabama.[73]

By the 1960s the Corps had conducted about 30 lock model studies on individual projects, WES efforts included, while the TVA had completed only six. These had kept pace with construction to that date. In spite of knowledge gained through research and construction, there were many gaps and serious questions left unanswered. For example, no general relationships had been developed between lift, filling time, depth of water in the lock chamber, and other factors. Nor were there reliable guides on the combination of lock size, lift, desired filling time, and potential filling system designs. On any lock where lift was about 20 feet, planners usually considered a model study necessary.[74]

By the early 1960s, however, the Corps had approximately 60 locks either under construction, planned, or authorized. Most were intended for large-scale, long-term canalization and navigation projects on the Arkansas, Ohio, Alabama, and other river systems. Because there was not time for site-specific investigations, the Corps needed standardized designs and procedures for a specific range of lock lifts, depths, and sizes.[75] Turning to WES, OCE consolidated its lock design program at the Station in late 1961 as Engineer Study 820, Lock Filling and Emptying Systems. Lock design then occupied an entire section of Brown's Hydrodynamics Branch. In 1963 this section split away to become part of a separate Structures Branch with Murphy as Chief. Branch efforts concentrated on developing standardized criteria for three lock sizes: 600 ft by 84 ft, 600 ft by 110 ft, and 1,200 by 110 ft.[76] WES-developed criteria soon found use in Corps locks on a national basis.

Francis Escoffier of the Mobile District helped point the WES lock program in a new direction. During the 1950s he had become intrigued with a "longitudinal floor culvert system" used for lock filling and emptying designs on the Rhone River in France. By the early 1960s Escoffier's interest in the French design intensified when the Mobile District became heavily involved in the design and construction of high-lift locks on the Alabama River. In visits to WES over a period of years, Escoffier had promoted the European method. WES engineers tended to favor the design in principle, but did not have time for extended studies and feared it would be excessively expensive. Undaunted, during one of Escoffier's visits to the Station, he and Murphy sketched out a modified version of the French-inspired lock system on the hood of a car. A.M. Cronenberg of the Mobile District then prepared detailed drawings for a cost estimate. The end product was a less elaborate and cheaper version of the French system feasible for the Alabama River's Millers Ferry Lock.[77] A WES model test series supervised by Murphy from 1962 to 1964 indicated that the floor culvert system was superior to the Corps' standard sidewall filling and emptying setups, especially for high-lift locks. Murphy, Jackson H. Ables, Jr., and Marden B. Boyd made further refinements that the Corps incorporated into the Millers Ferry and Jones Bluff Locks on the Alabama River and the Dardanelle Lock on the Arkansas River.[78] This scheme ultimately became the standard for high-lift locks on other projects on the Columbia River and on the Tennessee-Tombigbee Waterway.

Notes

1. Cotton, 27.

2. Henry L. Simmons, interview by Michael C. Robinson, typewritten transcript, WES Archives; also biographical information compiled by WES Public Affairs Office. Simmons' lack of formal education was not unusual. WES soil mechanics pioneer Joseph B. Compton had a degree from the University of Virginia in business.

3. See *Annual Summary of Investigations in Support of the Civil Works Program for Calendar Year 1950. Annual Summary No. 20* (Vicksburg: WES, 1951).

4. See, for example, "Report of the First Meeting of the Mississippi Basin Model Board," WES *Mississippi Basin Model Report No. 2-1* (Vicksburg: WES, 1945).

5. *Water Resources: Interview with Margaret S. Petersen*, interview by John T. Greenwood (Engineer Publication 870-1-60, 1998), 6-12.

6. Ibid. Also Margaret S. Petersen, River Engineering (Englewood Cliffs, New Jersey: Prentice-Hall, 1986).

7. A full discussion of MBM instrumentation is included in H.C. McGee, "Automatic Instrumentation of the Mississippi Basin Model," WES *Mississippi Basin Model Report No. 1-5* (Vicksburg: WES, 1955).

8. Ibid.

9. Ibid.

10. Details of verification are contained in a series of reports. See, for example, "Verification of Sioux City-to-Hermann Reach, Missouri River and Tributaries, 1950 and 1947 Floods," WES *Mississippi Basin Model Report No. 12-1* (Vicksburg: WES, 1952).

11. Foster, "History and Description of the Mississippi Basin Model."

12. A full account is contained in J. E. Foster and S. J. Ruff, "Comprehensive Testing Program, Hydraulic Model Investigation," WES *Mississippi Basin Model Report No. 29-1*, 8 appendixes (Vicksburg: WES, 1971).

13. Martin Reuss in *Designing the Bayous: The Control of Water in the Atchafalaya Basin, 1800–1995* (Alexandria, Virginia: Office of History, U.S. Army Corps of Engineers, 1998) provides a detailed account of the Corps' multifaceted involvement. An especially harrowing account of the 1973 near-disaster and of the Old River phenomenon in general is included in John McPhee, "Atchafalaya," Chapter 1 in *The Control of Nature* (New York: Farrar Straus Giroux, 1989), 3-95.

14. Robinson, "Rivers in Miniature," in Fowle, ed., 292.

15. "Preservation and Enhancement of Niagara Falls, Hydraulic Model Investigation," WES *Technical Memorandum No. 2-411* (Vicksburg: WES, 1955). A more general discussion is included in Andrew P. Rollins, Jr., and George B. Fenwick, "Model Studies of Remedial Works for Niagara Falls," *Transactions of the American Society of Civil Engineers* 124 (1959): 336-51.

16. "Preservation and Enhancement of Niagara Falls," WES *Technical Memorandum No. 2-411*.

17. Ibid.

18. Rollins and Fenwick, "Model Studies of Remedial Works for Niagara Falls," 245-51.

19. E.B. Lipscomb, "Preservation and Enhancement of Niagara Falls, Hydraulic Model Investigation. Appendix B: Restudy of Niagara Remedial Control Dam," WES *Technical Memorandum No. 2-411* (Vicksburg: WES, 1960).

20. A detailed account of the Corps' role in constructing the seaway is included in William H. Becker, *From the Atlantic to the Great Lakes: A History of the U.S. Army Corps of Engineers and the St. Lawrence Seaway* (Washington, D.C.: Office of the Chief of Engineers, 1984).

21. Ibid., 15-16.

22. A thorough account is included in George B. Fenwick, Willard F. Simpson, and Shields E. Clark, Jr., "Model Study for the Improvement of the Galop Rapids Reach of the St. Lawrence River," WES *Technical Memorandum No. 2-233* (Vicksburg: WES, 1947).

23. Ibid.

24. Earnest B. Lipscomb, "Surges in the Intermediate Pool of Long Sault Canal, St. Lawrence River," WES *Technical Report No. 2-489* (Vicksburg: WES, 1958).

25. Earnest B. Lipscomb and A.M. Gill, "Navigation Improvements in Barnhart Island-Cornwall Island Reach, St. Lawrence River, Hydraulic Model Investigation," WES *Technical Report No. 2-567* (Vicksburg: WES, 1961).

26. Becker, *From the Atlantic to the Great Lakes*, 100-04.

27. The Red River formed the southern boundary of Oklahoma and Texas, then flowed through Shreveport and Alexandria, Louisiana, on its course to the Mississippi. A few miles before the junction of the Red with the Mississippi at Turnbull's Bend, the Black River flowed into the Red. The Black in its upper reaches was known as the Ouachita River, which provided water access to north central Louisiana and southern Arkansas.

28. A comprehensive account of the Old River dilemma is contained in "Old River Diversion Control, A Symposium," *Transactions of the American Society of Civil Engineers* 123 (1958): 1129-181. Contributions therein include Major General John R. Hardin, "The General Problem," 1131-141; Eugene A. Graves, "Hydraulic Requirements," 1142-159; Willard J. Turnbull and Woodland G. Shockley, "Foundation Design," 1160-171; and Norman Moore, "Structures Required," 1172-181. A more general sketch is contained in Major General John R. Hardin, "Mississippi-Atchafalaya Diversion Problem," *The Military Engineer* 46 (1954): 87-92.

29. A detailed account of the Old River controversy, including its political and engineering ramifications, is contained in Martin Reuss, *Designing the Bayous: The Control of Water in the Atchafalaya Basin, 1800–1995.*

30. See Captain Dan C. Kingman, "Upon Operations in the Fourth District," Pt. 4, *Annual Report of the Chief of Engineers, United States Army*, (U.S. Govt. Printing Office: Washington, 1888), 2298. Kingman reported that "I have given the Atchafalaya problem much thought and study....The dangers to be averted and the obstacles to be overcome are, so far as the Mississippi River is concerned...the deflection of its waters in ever-increasing quantities down the Atchafalaya which might in time, due to its shorter length, exceed in capacity the main stream and finally become the sole outlet of the Mississippi."

31. D.O. Elliot, *The Improvement of the Lower Mississippi River for Flood Control and Navigation* (Vicksburg, WES: 1932), 1: 50-57; 2: 313-315.

32. Special insight concerning the Baton Rouge organization and its move to Vicksburg is provided in William B. Steinriede, interview by author, Vicksburg, 11 June 1992.

33. Harold N. Fisk et al., *Geological Investigation of the Atchafalaya Basin and the Problem of Mississippi River Diversion* (Vicksburg, MRC: 1952) 2 vols. Also John R. Hardin, "Mississippi-Atchafalaya Diversion Problem."

34. "Old River Closure Structures; Model Investigation," WES *Technical Memorandum No. 2-276* (1949).

35. "Old River Control Structure Sediment Diversion, Hydraulic Model Investigation," WES *Technical Memorandum No. 2-388* (Vicksburg: WES, 1954).

36. "Geology of Old River Closure Control Structures and Lock Site," WES *Technical Memorandum No. 3-305* (1949).

37. *Geologic Studies for Control Structures, Vicinity of Old River* (WES, Vicksburg: 1953), unpublished.

38. "Old River Low-Sill Control Structure, Downpull Forces on Vertical-Lift Gates, Hydraulic Model Investigation," WES *Technical Report No. 2-447, Report 1* (Vicksburg: WES, 1956); "Old River Overbank Structure, Forces on Panel Gates, Hydraulic Model Investigation," WES *Technical Report No. 2-491* (Vicksburg: WES, 1959); and J.H. Ables, Jr., and F.R. Brown, "Filling and Emptying System, Old River Navigation Lock, Louisiana, Hydraulic Model Investigation," WES *Technical Report No. 2-549* (Vicksburg: WES, 1960).

39. "Resume of Conference Initiating Potamology Investigations," WES *Potamology Investigations Report No. 11-0* (Vicksburg: WES, 1947).

40. "Instructions and Outline for Potamology Investigations," WES *Potamology Investigations Report No. 1-1* (Vicksburg: WES, 1947); "Outline of Plans for the Potamology Investigations," WES *Potamology Investigations Report No. 1-2* (Vicksburg: WES, 1947); and J.B. Tiffany, *Review of Research on Channel Stabilization of the Mississippi River, 1931-1962* (Vicksburg: WES, 1962).

41. See "Report on First Potamology Conference with Hydraulics Consultants," WES *Potamology Investigations Report No. 11-2* (Vicksburg: WES, 1948); and "Report of Second Potamology Conference with Hydraulics Consultants," WES *Potamology Investigations Report No. 11-4* (Vicksburg: WES, 1949).

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54. Ibid., and *Report of First Conference on Cavitation with Hydraulics Consultants* (Vicksburg: WES , 1949). Also see, *Report of First Conference with Hydraulics Consultants on Effects of Model Distortion on Hydraulic Elements* (Vicksburg: WES, 1949), *Report of First Conference with Hydraulics Consultants on Roughness Standards for Hydraulic Models* (Vicksburg: WES, 1949), and *Operating Forces on Miter-Type Lock Gates* (Vicksburg: WES, 1964).

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57. See "Model Study of Wave and Surge Action, Naval Operating Base, Terminal Island, California," WES *Technical Memorandum No. 2-237* (Vicksburg: WES, 1947).

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6 Hydraulics Research Giant, 1949-1963, Part II: Tidal Estuaries and Nuclear Weapons Effects

New Frontiers in Tidal Estuary Modeling

Work in tidal hydraulics, especially pertaining to estuaries, represented the most innovative area of research by the Hydraulics Division in the two decades after World War II. In the 1930s and through the war years, WES had pioneered harbor model studies — Ballona Creek, Maracaibo Bay, East River, San Pedro Bay, Alameda, Midway, and others — that incorporated tidal factors. During that span WES developed new experimental equipment such as automated tide machines and measuring devices that allowed reasonably accurate reproduction and quantification of tidal phenomena. Postwar efforts turned to increasingly more complex tidally-influenced prototypes: tidal estuaries. Unlike saltwater harbors, estuaries are the "meeting places" for salt and freshwater. Numerous interrelated factors shape a typical estuary: rising and falling tides, waves, different densities of fresh and salt water, sediments, winds, littoral currents, turbulence caused by ships, and many other factors combine to form one of the world's most complicated ecological and engineering environments.[1]

In early studies at WES and elsewhere, two elements of estuary behavior especially challenged engineers: saltwater intrusion and shoaling. Both resulted largely from the different densities of saltwater and freshwater. Because saltwater is denser than fresh, the two resist mixing except in the case of highly turbulent flows.

In nature, when small volumes of freshwater flow into an estuary at low velocity via a stream, the freshwater will remain on top of the saltwater and flow slowly seaward. There will be no appreciable mixing of freshwater and saltwater at all. With increased freshwater discharges, as from a larger stream, the freshwater pushes the saltwater away from the landward end of an estuary. The saltwater layer will then assume the shape of a wedge with the sharp edge pointed toward the source of freshwater velocity. Still, almost no mixing takes place and there will be a distinct interface between the freshwater and saltwater layers. In this "highly stratified" condition, the saltwater wedge will move upstream beneath the freshwater during high tides and retreat downstream during low tides. Since the current is essentially the product of the density difference between the two, it is called a "density current." The extent of saltwater "intrusion" upstream depends on the volume of freshwater discharge, channel depth, and other factors. In the case of the Mississippi River, saltwater intrusion from the Gulf of Mexico sometimes extends inland as far as New Orleans, over 100 miles upriver. Saltwater intrusion in any populated river system threatens drinking water supplies, irrigation, industrial processes, and ecological balances.

Density differences between salt and freshwater can also have profound impacts on the direction, magnitude, and duration of currents in open areas of estuaries such as harbors. These density currents are also typically affected by other factors such as tides and winds. Of particular concern to engineers, currents are the primary mechanism of shoaling. In its simplest form, shoaling involves the picking up of deposits by water, their transportation by currents to another location, and their deposition there. Shoals threaten navigation and often cause fundamental changes to hydraulic environments. American engineers had long studied shoaling in rivers and non-estuarial harbors, such as the Mississippi River and Mare Island Strait, but shoaling forces affected by density currents in estuaries proved much more complex.

Saltwater Intrusion: Lower Mississippi River

The first WES saltwater intrusion study dealt with the movement of saltwater from the Gulf of Mexico into the lower reaches of the Mississippi River. As a highly-stratified system, almost no mixing of fresh and saltwater took place at the mouth of the Mississippi. A classic saltwater wedge formed the bottom layer of a two-layered structure, with the upper layer having zero salinity. During periods of low freshwater flows in the Mississippi, a saltwater wedge at times migrated upriver far enough to contaminate the water supply of New Orleans. By 1941 the New Orleans District had proposed a number of possible remedial measures, including construction of sills on the bottom of the river or of a floating barrier dam.

WES conducted model experiments to determine the efficacy of the proposed plans. Almost no data existed concerning the behavior of fresh and saltwater when mixed, and attempts to introduce both fresh and saltwater into a model would represent a radical departure from previous WES model studies. Simmons and Hudson first supervised tests in a glass flume to try to determine model laws relative to the movement of saltwater through freshwater. Using observations from these tests, they developed the first criteria and scales to design and operate a distorted saltwater intrusion model.[2]

By early 1942 WES had constructed a model representing a 40-mile stretch of the Mississippi River below New Orleans where remedial works were projected. Model operation consisted essentially of introducing freshwater flows into the upper end of the model to correspond to daily flows recorded during the low-water season of 1940. Saltwater dyed with potassium permanganate was then introduced at the lower end of the model, with flows again correlated with field measurements. Salinity exactly matched that of the prototype. Visual observation and an electrically operated salinity meter designed at the Station enabled engineers to track the movement of saltwater through the model and to determine the interface between salt and freshwater. Tests consistently reproduced the rate of upstream progress and elevations and locations of the prototype saltwater wedge. Considering the model verified, project personnel conducted experiments adding the proposed sills and barrier dam, all of which indicated that the structures would not be effective in preventing intrusion.[3]

The WES findings were not readily accepted. Grave doubts existed as to the accuracy of the model tests largely because the methods used contradicted earlier theories advanced by Morrough P. O'Brien and John Cherno.[4] There was speculation that the study was incomplete and even that the correspondences between the model and prototype were only accidental.[5] OCE consequently asked the Bureau of Standards to evaluate the WES tests and to establish more precise laws pertaining to density currents. In 1945 Garbis H. Keulegan of the Bureau's Hydraulic Laboratory in Washington, D.C., began a lengthy series of investigations. These resulted in the publication of 14 major reports, many sponsored by WES, that profoundly influenced estuary modeling. After initial reservations Keulegan essentially supported the WES methods used in the Lower Mississippi saltwater intrusion model.[6]

Garbis H. Keulegan and WES


Garbis H. Keulegan

Keulegan's density current tests marked only the beginning of a long and near-legendary relationship with WES. Born in Sebastia, Armenia, in 1890, Keulegan was the son of an Armenian engineer father and German mother. He graduated from Anatolia College in 1910, then two years later emigrated to the United States in search of higher education. For most of a year he worked at odd jobs, including stints at Ford and Cadillac automobile factories, before matriculating at Ohio State University. Ironically, he never learned to drive a car.[7]

Keulegan earned two bachelor's degrees from Ohio State University, then worked for a short time for Westinghouse Electrical and Manufacturing Company. At the entry of the United States into World War I, he volunteered for military service even though he was not yet an American citizen. Due to his travels, linguistic abilities, and classic education, he was fluent in Armenian, Turkish, German, French, and English, and could read Greek and Latin – talents that led to his appointment as a translator on General John J. Pershing's American Expeditionary Force staff in France. At the war's end in 1918, he learned that the Turks had occupied and destroyed his home city and that almost his entire family, including five younger siblings, had been massacred. One brother, studying in Paris, was the only survivor. This solidified his decision to remain in the United States, which had already granted him citizenship that same year.

Keulegan joined the staff of the National Bureau of Standards in Washington, D.C., in 1920. He concurrently pursued graduate studies in mathematical physics at Johns Hopkins University that lead to a Ph.D. in 1928. At the establishment of the Bureau of Standards National Hydraulic Laboratory in 1932 he became one of the members of the original staff. There he conducted studies on a wide variety of subjects including flow-through conduits, boundary layer development, open channel flow, stratified flow, natural waves, gravity waves, wind action, viscosity, and others. Keulegan's contributions to the institution were of such magnitude that Rouse and Ince in their *History of Hydraulics* stated that "the laboratory [U.S. Bureau of Standards] gained its scientific repute through the writings of one man, Garbis Hovannes Keulegan, in the field of fluid mechanics."[8] Of special note, Keulegan's *Laws of Turbulent Flow in Open Channels*, published by the Bureau of Standards, became a classic in the field.

In 1960 Keulegan reached the then mandatory retirement age of 70. Two, one-year presidential extensions allowed him to complete a beach erosion study he was conducting for the Bureau of Standards. Already, he had wondered aloud on occasion to Henry Simmons (who monitored Keulegan's studies for WES performed at the National Hydraulic Laboratory) as to what he might do to remain professionally active. Simmons encouraged him to come to WES, an idea that got the enthusiastic support of Hydraulics Division Chief Fortson and Station Director Colonel Edmund Lang. In 1962 Keulegan accepted an offer from WES Technical Director Tiffany to accept a position as a resident consultant in hydraulics and hydrodynamics. Station lore maintains that Keulegan insisted on three specific clauses in his contract: he would consider only those problems that interested him; he would work on them only when he felt so inclined; and there must always be a green tree outside his window. The Department of the Army, however, at first denied the Station's request to hire Keulegan because of his age. After several further requests and justifications, WES finally received clearance in October 1962 to hire Keulegan on a half-time basis for one year.

Keulegan's relocation to Vicksburg, according to many who worked with him, had a catalytic and inspirational effect.[9] A rare combination of genius and humility, in his enthusiasm for solving complex engineering problems he was fond of saying that his favorite project was "The one I'm working on." Despite his lack of training in computer methods, by the end of the 1960s he was helping lead WES toward hydraulic numerical modeling. In 1968 he received the National Medal of Science, in 1969 a prestigious Army Research and Development Achievement Award for his work on design of protective structures against damage from tsunamis, also in 1969 Honorary Membership in the American Society of Civil Engineers, in 1973 the Meritorious Civilian Service Award, and in 1979 he was elected to the National Academy of Engineering. Although his original intent was to work at WES for two years, extensions granted by the Army enabled the world-renowned scientist to serve the Station with distinction until retiring for the second time in 1988 at the incredible age of 98. He died less than one year later.

Savannah Harbor Study

While Keulegan pursued investigations of saltwater intrusion at the Bureau of Standards, studies for navigation improvements in Savannah Harbor, Georgia, pushed modeling of tidal estuaries to new limits. In the late 1930s commercial interests pressed for construction of an enlarged and extended jettied channel from the mouth of the Savannah River to deep water in the Atlantic Ocean. Ralph F. Rhodes, head engineer of the Savannah District, emerged as a vociferous proponent. In addition to the locally desired navigation enhancements, Rhodes insisted that plans include contingencies to reduce maintenance dredging in portions of the harbor subject to heavy shoaling. Owners of beachfront property also wanted projects for beach erosion control. Since it was not known how such sundry alterations would affect the harbor as a whole, in 1940 the Savannah District Engineer requested a WES model study. Interrupted by war, the Hydraulics Division did not complete the project until June 1946.[10]

Savannah Harbor model, 1946

The estuary represented the single most complex hydraulically active area replicated by WES to that date. A fixed-bed model miniaturized approximately 355 square miles of prototype area, including 50 miles of the Savannah River (up to the limit of tidal influence), an extensive system of other tidal tributaries, the harbor proper, all channels, bank and overbank features, islands, and the adjoining part of the Atlantic Ocean. Two improved automatic tide machines and state-of-the-art measuring equipment completed the model.[11]

Rhodes and WES engineers involved in the project held high hopes that verification tests of the model would reproduce field measurements of the complex current velocities and directions in the harbor. Prototype currents appeared puzzling if not outright contradictory in several respects. Surface and bottom currents, for instance, were often in opposite directions. Amid sizeable excitement, project engineers filled the completed model with freshwater and started the inflow and tidal apparatuses. Measurements of current velocities and directions in the model, unfortunately, were totally confounding. No matter how the model was operated, it would not reproduce conditions in the prototype.

Finally Tiffany suggested to Fenwick and Simmons, the engineers in direct charge, that water with the same salinity as that of the prototype ocean be used in the model ocean rather than freshwater. Model operators then developed a technique to determine the correct ratio of salt to freshwater to be used in the model as a whole and methods to introduce each to prevent undue mixing. Efforts were complicated in that, unlike highly stratified estuaries such as the Lower Mississippi River, where there was no significant mixing of salt and freshwater, sufficient forces existed in Savannah Harbor to produce a partly mixed condition. The interface was not so clearly defined and density currents were more complex. Continued experimentation and addition of roughness improved performance so that the model finally reproduced field observations accurately. For the first time in the United States, hydraulic engineers had devised a model and operating techniques that could reproduce intricate density currents in an estuary. Researchers further realized that density currents played a much more important role than hitherto discerned in estuarine hydraulics.[12]

Committee on Tidal Hydraulics

The Savannah Harbor project had repercussions throughout the Corps. Concerned over the primitive state of understanding of tidal hydraulics the model exemplified, Tiffany, Rhodes, and Clarence F. Wicker of the Philadelphia District pushed for the establishment of a coordinated Corps research program. (Wicker's involvement stemmed from WES's concurrent construction of a model for a major study of saltwater intrusion and shoaling in the Delaware River estuary.) In 1947 WES Director Hardin formally proposed to the

Committee on Tidal Hydraulics, Philadelphia, PA, 1949 (from left): Berkeley Blackman, Martin A. Mason, Boris A. Bakhmateff, James R. Johnson, Richard O. Eaton, Jacob H. Douma, Clarence F. Wicker, Ralph F. Rhodes, Joseph B. Tiffany, Lorenz G. Straub, Oscar Rosenzweig

Committee on Tidal Hydraulics, Vicksburg, 1955; WES personnel: Joseph B. Tiffany (first row, third from left), Henry B. Simmons (first row, last on right), Eugene P. Fortson (third row, first on left), George B. Fenwick (third row, third from left); Garbis H. Keulegan (second row, second from left) joined WES later

Chief of Engineers that research funds be made available for such an approach. The following year Wicker further suggested that OCE establish a Committee on Tidal Hydraulics to direct research and disseminate information to the Corps as a whole. Acting on Wicker's proposal, OCE committed the Corps to a coordinated tidal hydraulics research effort by ordering the founding of the Committee in October 1948.[13] The Committee on Tidal Hydraulics continues to guide Corps efforts in that area.

From its inception, the Committee displayed a strong WES influence. Tiffany was a founding member, serving as recorder from 1949 to 1958, chairman from 1962 to 1969, and as a consultant after 1969. Simmons joined Tiffany on the committee in 1954, remaining until 1968 when he also became a consultant. Frank A. Herrmann of WES became a member in 1971. Other original members with WES ties included Rhodes and Wicker, with the latter serving as first chairman.[14]

In January 1949, at its first meeting in Washington, D.C., the Committee decided to hire outside specialists and consultants, again tying the Corps to the most eminent academicians in the United States. (The second meeting, in March 1949, was at WES.) Bakhmeteff and Straub, both of whom already served as consultants for WES in its potamology investigations, accepted positions. Arthur T. Ippen of MIT, Donald Pritchard of Johns Hopkins, Ray B. Krone of the University of California at Davis, and Hans Einstein of the University of California at Berkeley also later served as Committee and WES consultants, and Keulegan served as a Committee consultant both before and during his employment at WES.[15]

The membership, after agreeing that a concerted effort was urgently needed in tidal hydraulics, conducted a survey of the state of the art published by WES in February 1950. Simmons was a valuable contributor, authoring a section on use of hydraulic models in tidal studies.[16] By 1954 the Committee had compiled and eventually published a bibliography on tidal hydraulics, with 10 supplements, through 1986. In a long-term research initiative, the Committee sponsored studies at WES and at the Corps' Coastal Engineering Research Center (CERC), then located at Dalecarlia Reservoir in Washington, D.C., and later at Fort Belvoir. This resulted in publication of more than 20 technical bulletins and over thirty reports on results of site-specific studies, with much of the work performed at WES.[17] In a short time, the Station had become one of the most important centers of tidal hydraulics research in the United States.

Delaware River Studies

The Delaware River estuary study, performed for the Philadelphia District, proved even more difficult than its Savannah Harbor predecessor. Project objectives involved both navigation and environment concerns. Since maintenance of the widths and depths of the navigation channel in the commercially vital area required substantial dredging, the investigation was to determine the effectiveness of proposed dikes, channel realignments, and other improvements to prevent shoaling. Any alterations had to take saltwater intrusion into consideration, as intrusion already constituted a serious problem upriver almost to Philadelphia. Industrial and municipal wastes discharged into the estuary were also problems of increasing magnitude.[18]

Hydraulically, the prototype displayed an unusual set of conditions. Sufficient river velocities and other turbulence-producing elements combined to create a well mixed estuary. Except in rare instances, a definite interface between salt and freshwater did not exist at all, and salinity intrusion did not occur as the advancement of a well-defined saltwater wedge beneath a freshwater layer. Nonetheless, surface salinities were less than bottom salinities at any given location, so that current velocity measurements showed characteristics similar to, but less prominent than, those of partly mixed estuaries like Savannah Harbor. Salinity also increased from the mouth of the Delaware River into Delaware Bay, making model verification even more complex.

After analyzing prototype data for almost two years, WES began construction of the Delaware River estuary model in September 1948. Upon completion in February 1949, the impressive edifice stretched approximately 750 feet in length and covered 30,000 square feet. Reflecting a trend exemplified first by the Mississippi River Flood Control Model and later by the Mississippi Basin Model and the Savannah Harbor Model, the Delaware River structure was intended for long-term use and for a wide range of experiments. Designers anticipated a life of 15 to 20 years.

Delaware River model

As in the original Savannah Harbor model tests, early attempts to verify the Delaware River model were not successful. Saltwater intrusion was considerably greater in the model than in the prototype, model surface salinities were too low, bottom salinities too high, and current velocities near the bottom of the model were incorrect. Simmons concluded that roughness in the model bed did not produce enough turbulence to vertically mix the saltwater and freshwater in the model to the extent they were mixed in the prototype. He then had new resistance elements installed consisting of 0.5-inch to 0.75-inch-wide metal strips set vertically in the model bed with the top of each strip at about the elevation of mean low water. Workmen first placed an excessive number of strips, then bent them down or up as necessary until measurements indicated that tidal phenomena and current velocities were reproduced accurately throughout the model. Further rearrangements resulted in reliable duplication of saltwater intrusion and vertical distribution of salinity. This simple solution found use in numerous other models.[19]

Charleston Harbor Shoaling

A third major WES estuary study embodied construction and operational techniques developed in its Savannah Harbor and Delaware River predecessors. Prior to 1942, shoaling in Charleston Harbor, SC, had been troublesome but not critical. But in that year a phenomenal increase in the rate of shoaling began in the inner-harbor navigation channels. By 1953 the gross annual shoaling rate had grown from 120,000 cubic yards to 4.3 million cubic yards, a 36-fold increase that necessitated constant and expensive dredging. The Charleston District requested a WES model study to determine the cause or causes of shoaling and to help develop preventive measures. Initial field work began in late 1947, with the model study completed in March 1953.[20]

Two changes in the estuary's regimen had preceded the increase in shoaling and they were assumed, either singly or in combination, to be the sources of difficulty. First, a navigation improvement program had deepened the harbor's entrance channel from 30 feet to 35 feet, and


Charleston Harbor model

second, construction and operation of the Santee-Cooper Power Project had greatly increased the discharge of freshwater into the harbor via the Cooper River. Extensive model tests, using gilsonite to simulate shoaling materials, showed that the channel deepening had little if any influence. Samples taken from the harbor further indicated that almost all of the shoaling materials were clays transported by the Cooper River and were not from the harbor bed. Project engineers Simmons and T.J. Kinzer, Jr., then faced the quandary of determining how increased freshwater flows could result in such monumental shoaling.

Reproduction and analysis of density flows revealed a surprising set of conditions. Increased river flows had scoured the bed of the Cooper River to new depths. As the river entered Charleston Harbor, upstream density currents near the bottom occurred as a result of salinity intrusion. Clay sediments transported as a side effect of the Santee-Cooper project, traveling along the deepened bottom of the river, were blocked by the density currents and prevented from sweeping into the open harbor or sea. Contact between clay sediments and saltwater also resulted in the complex and controversial phenomenon of flocculation, or aggregation of many tiny grains into larger particles, so that huge quantities of clays were deposited as shoals.

Tests of proposed preventive measures led to adoption of a troublesome and expensive, but effective, solution. Rerouting part of the Santee River's flow back into the Santee basin enabled the Charleston District to control shoaling and increase dredging efficiency. Of primary importance, the Charleston Harbor model again demonstrated the value of estuary models and showed that new ideas and techniques could be applied to unexpected situations. By the mid-1950s modeling of tidal estuaries had entered a new phase as the result of lessons learned from the Savannah Harbor, Delaware River, and Charleston Harbor projects.

Multiple Uses for Estuary Models

Although designed primarily to study saltwater intrusion and shoaling phenomena, estuary models found multiple uses over extended periods of time. This pertained not only to the Savannah Harbor, Delaware River, and Charleston Harbor models, but by the late 1950s to newer models of New York Harbor, San Francisco Bay, Narragansett Bay, and other locations. Studies in most dealt with tidal flushing, pollution and contamination dispersion, and related topics, but were also extended to specialized investigations such as the effects of hurricane surges.[21]

WES began its first pollution-related study in December 1956 using the Delaware River model. The effort represented one of the Station's few jobs performed for a private client. Located on the New Jersey shore of the Delaware River across from Philadelphia, the Gloucester City plant of the New Jersey Zinc Company discharged plant waste into an abandoned slip next to the plant site. Much of the heavier-than-water waste passed from the slip into the river. Current velocities adjacent to the shoreline were so low that a considerable part of the effluent, rather than being dispersed, was concentrated in small embayments and pockets along the New Jersey shore in the vicinity of the plant. The company proposed to construct a pipeline to transport plant waste directly to the bottom of the river in the navigation channel, where current velocities were higher and would carry the effluent to sea.[22]

The Estuaries Section, in performing a study to determine the efficiency of the proposal, developed techniques used in numerous later investigations. These involved simulating plant wastes with a tracer of the same average concentration and average specific gravity as the effluent in the prototype. After a number of experiments using potential tracers, methylene blue chloride emerged as the most effectual choice. Tests on a continuing basis provided details as to how tracers should be prepared, introduced into the model, traced throughout the model, and analyzed after model operation.[23]


New York Harbor

Hudson River and New York Harbor Studies

Construction and operation of a huge model of the entire New York Harbor complex exemplified the multiple functions of estuary models. By the mid-1950s shoaling along the Lower Hudson River significantly interfered with commerce. Constant dredging was necessary to keep waterfront slips open to deep-draft ships. In some cases, especially in the Edgewater, New Jersey, waterfront, businesses had actually been forced by economic considerations to move elsewhere, leaving plants unoccupied.

Responding to commercial demands, in early 1957 the New York District asked WES to perform a model study, reproducing tides, tidal currents, density currents, and shoaling in the entire New York Harbor area to evaluate plans for reducing dredging. Various proposals involved channel realignments, sediment basins, dikes, closure gates, and other measures. Model tests were also to determine the effects of any remedial actions on hydraulic conditions in the region such as salinity.[24]

Simmons, Kinzer, and William H. Bobb designed and supervised construction of an estuary model that again pushed WES techniques to new limits. Reproducing the tidal portions of all significant tributaries of New York Harbor and the Hudson River as far upriver as Hyde Park, the facility incorporated an intricate network of miniature piers, docks, slips, bridges, and other prototype structures. Anticipating that the model would be used for other purposes, designers correctly reproduced all elevations in the prototype area up to about 25 feet mean sea level (msl) so that the effects of hurricane surges could be studied in the future.[25]

The New York model produced multiple benefits, eventually being used in more than 30 projects. Shoaling studies continued through 1965, leading to implementation of remedial plans, while

concurrent tests dealt with entirely different problems. In 1958, the model's second year of operation, the Nuclear Projects Office, Maritime Administration, U.S. Department of Commerce, funded a study pertaining to the dispersal of radioactive wastes that might be released either accidentally or purposely into rivers, estuaries, and harbors. As in the Delaware River contamination tests, operators of the New York Harbor model used methylene blue chloride dye as a tracer to arrive at projections.[26] A 1960 test series for the Interstate Sanitation Commission determined New York Harbor dispersion characteristics for the 135 sewage treatment plants in the prototype area.[27] The model also served to predict hydraulic, shoaling, and pollution dispersion effects resulting from pile-supported runway extensions at LaGuardia Airport.[28]

In addition to the New York Harbor radioactive waste tests, WES performed similar studies for the Nuclear Projects Office on the existing Delaware River and Narragansett Bay models at the Station and supervised tests using the San Francisco Bay model at Sausalito, California.[29] The last was unusual in that, due to strong local interest, it was one of the few Corps models located on site rather than at WES. Constructed in 1956 and 1957 inside a World War II-vintage shipbuilding warehouse, it was one of the world's largest estuary models.[30] Although the San Francisco District built and nominally operated the facility, WES personnel acted as general directors of tests to determine dispersion patterns of radioactive wastes. These took advantage of experiences gained in previous investigations at the Station and led to a significant improvement in testing techniques. The New York, Delaware River Estuary, and Narragansett Bay models used methylene blue chloride dye as a tracer. Never considered ideal, it required photometric analysis that was greatly complicated by the varying turbidity of water in a model. WES engineers had discussed the use of fluorescent dyes as replacements, but instruments for measuring fluorescence were not available. During the San Francisco tests, G.K. Turner Associates of Palo Alto, California, worked with Corps personnel to develop a fluorometer that could measure concentrations of fluorescent dyes. Use of fluorometric techniques then greatly simplified sample analysis and data processing.[31]

Frederick R. Brown

Military Research: Nuclear Weapons Effects

Military-related research by the Hydraulics Division declined precipitously in the aftermath of World War II with one major — and totally unanticipated — exception. With the development of nuclear weapons by the Soviet Union, American strategists were concerned about the possible effects of nuclear explosions in water. The advent of a nuclear explosion in New York Harbor or in the Mississippi River, for example, would have unknown consequences.

In early January 1951 OCE inquired by telephone as to WES's capability to perform a study of underwater explosion phenomena for the Armed Forces Special Weapons Project (AFSWP; later redesignated Defense Atomic Support Agency). Tiffany and Brown subsequently hurried to the Pentagon for a series of conferences after which the AFSWP announced that WES would perform the project. Further conferences at WES in February extended the scope of study to include measurements of cratering in different soils media, water surface waves, air blast, water shock, and ground shock. Because of classified aspects of the work, the project was simply referred to as the "2178 Study" from its job number.[32]

Within the Hydrodynamics Branch, Brown formed a Special Investigations Section under Guy L. Arbuthnot, Jr., to conduct experiments, with John N. Strange also playing a key role. A.B. Arons of Amherst College headed a group of consultants that gave assistance and advice during the initial phases of the study.[33]

Large test basin used in early underwater blast tests, 1951

Within a matter of weeks in 1951 WES constructed a large earthen test basin at a remote area of the reservation. About 350 feet long, the keyhole-shaped facility could be filled with water to a depth of 5 feet, then quickly drained with floodgates. In August a series of tests began that were aimed at determining the effects of different magnitudes of explosions at various water depths. TNT charges of 0.5, 4, 8, 16, and 32 pounds simulated nuclear explosions at depths in the model representing up to 200 feet in a prototype. Engineers set charges at desired depths simply by attaching them to posts driven into the ground when the basin was empty. Charges were limited to 32 pounds due to concerns for nearby residential areas.[34]

WES engineers quickly realized that the instrumentation available at the Station was not capable of recording precise measurements pertaining to blast and shock phenomena. A search of commercially available products from private industry was also fruitless. It was therefore necessary for WES instrumentation specialists to develop the needed experimental equipment posthaste. In a crucial part of the explosive program, F.P. Hanes and L.H. Daniels of the Instrumentation Branch devised photographic, wave rod, and other apparatuses, along with methods of operation, that made accurate data collection possible.[35]

Tests in 1952 and 1953 were performed at remote natural sites in addition to the man-made basin. Off-reservation locales afforded a variety of soil conditions and allowed use of larger explosives. An old channel of the Mississippi River near Diamond Cutoff, about 10 miles south of Vicksburg, served as an exceptionally useful site,

Instrumentation developed by WES for underwater blast tests

with deep deposits of sand and more than three miles from the nearest habitation. Other abandoned channels at Delta Point, Mississippi, and Sorrento, Louisiana, had clay bottoms. Charge weights of 256, 600, and 2,048 pounds dwarfed explosions from reservation tests.

The WES investigation attempted to provide site-specific projections in addition to general interpretations of nuclear blasts in water. By 1952 the Soils Division completed a survey, based on existing boring data, of soil conditions at 12 coastal harbors in the United States. Locations profiled included New York, Boston, Philadelphia, New Orleans, Los Angeles, and San Francisco. Combining soils and hydraulic data with extrapolations from WES explosive tests, military analysts hoped to determine with at least some degree of accuracy the damage a nuclear explosion would cause at a particular harbor site.[36]

Nuclear Weapons Effects Division

Arbuthnot's Special Investigations Section enlarged its scope of activities through the 1950s. In a project for the Navy in 1953, a WES group led by F.A. Pieper took measurements of water shock, waves, and cratering resulting from the explosion of 90,000 pounds of TNT at Sevier Bridge Reservoir, Utah. At the time, it was the largest non-nuclear underwater explosion ever produced.[37] Further experiments for the Navy on the effects of nuclear explosions in deep water led to development of a new test site near Vicksburg on the Big Black River. With a test basin approximately 22 ft deep, surrounded by improved instrumentation largely suspended from poles and cables in the blast area, the facility defined the state of the art.[38]

In the late 1950s and into the 1960s the resumption of nuclear testing, ostensibly for peaceful purposes, resulted in even more WES involvement in explosive effects research. Activities involved engineers from many disciplines and various WES divisions. Increasingly, projects had less to do with hydraulics than with other fields such as structural engineering and soil mechanics. This evolution prompted administrative overhauls. In 1962 a Nuclear Weapons Effects Branch under Arbuthnot formed within the Hydraulics Division as an equal to the three existing branches. A year later Station Director Colonel Alex G. Sutton, Jr., removed explosive research entirely from the Hydraulics Division by creating a separate Nuclear Weapons Effects Division. (WES then encompassed five research divisions: Hydraulics, Soils, Concrete, Mobility and Environmental, and Nuclear Weapons Effects.) Brown, longtime head of the Hydrodynamics Branch, became chief of the new entity. As in the case of soil mechanics, activities that had begun in the Hydraulics Division resulted in the establishment of an entirely new division and the further enhancement of the Station's mission.

WES Starts its Fourth Decade: An Overview

At the end of 1960 WES began its fourth decade of experimental research. Taking stock, a survey of projects in progress at that time reveals both another tremendous increase in the Station's workload and the changing focus of hydraulic research since 1950. From 42 projects in 1950 (see listing in Chapter 5), the Hydraulics Division again almost exactly doubled its activities, engaging in a total of eighty-three projects in late 1960 (a complete listing, with sponsors, is included in Appendix B). Whereas flood control and river navigation concerns had dominated the majority of the Station's early efforts, in 1960 only three site-specific flood control studies were underway — Hoosic River, Massachusetts; Lower Atchafalaya River, Louisiana; and Turtle Creek, Pennsylvania — in addition to the operation of the Mississippi Basin Model. A mere three projects dealt with traditional river navigation: two on the Arkansas River and one on the St. Lawrence. However, the burgeoning WES lock and dam design program, then engaged in 17 site studies, indicated the shifting priorities of river navigation engineers.[39]

While flood control and some aspects of river navigation work declined, efforts increased in the areas of harbor and estuary improvement and protection. Large-scale model studies of the

Delaware River estuary; Galveston Bay, Hudson River, Narragansett Bay, Gulf Outlet Channel, Matagordo Ship Channel, Savannah Harbor, and Southwest Pass, shaped the Corps' harbor navigation programs at those locations. Related rubble-mound breakwater projects ranged from Morro Bay to Nawiliwili Harbor. At the same time, OCE Civil Works Investigations performed at WES contributed to the Corps' harbor and estuary engineering activities on a broader scale. These included investigations entitled "Tides and Currents in Tidal Waterways," "Mathematics of Flow in Tidal Inlets," "Shoaling Processes," "Salinity Intrusion and Related Phenomena," "Stability of Rubble-Mound Breakwaters," and "Effects Scale and Operating Techniques on Harbor Wave Action and Breakwater Models."[40]

WES activities in the design of dams and appurtenant hydraulic structures kept pace with the expanded harbor and estuary programs. Twenty site-specific studies involved edifices as far flung as Everett Dam, New Hampshire; Big Bend Reservoir, South Dakota; and Black Butte Dam, California, while four OCE CWI initiatives produced general hydraulic structures design criteria.[41]

Professional Developments

Growth of professional organizations in the post-World War II era reflected the burgeoning importance of hydraulic engineering. In numerous cases WES personnel played central roles. By 1956 the ASCE's *Transactions* had become so ponderous and meetings so unwieldy that the venerable association, in its 82nd year of existence, split its publishing and organizational operations into a divisional format. By that time the ASCE already encompassed two hydraulics-oriented divisions: the Hydraulics Division, founded in 1938; and the Waterways and Harbors Division. Both thereafter enjoyed the benefits of separate journals and newsletters and more autonomous and influential executive committees. WES connections were numerous. Tiffany and former Mississippi Basin Model Branch Chief Dewey formed two-thirds of the original membership of the Hydraulics Division's Committee on Publications, with Dewey as Chairman. In 1958 and 1959 Tiffany served as Secretary of the Division's Executive Committee while maintaining membership on the Publications Committee. Fortson succeeded Tiffany on the Executive Committee in 1960, serving as Chairman in 1962. Brown replaced Fortson on the Executive Committee in 1964, rising to Vice Chairman in 1967 and Chairman in 1968. Other WES engineers, including Simmons and Campbell, played prominent roles on subcommittees, while Ellis B. Pickett and Arbuthnot edited the division's *Newsletter*. Caldwell served on the Waterways and Harbors Division's Publication Committee from 1956 until 1965, while former WES researcher J.F. Friedkin acted as Vice Chairman in 1963.

WES influence was also prominent in the ASCE's Committee on Tidal Hydraulics, founded in 1954. The Corps' Committee on Tidal Hydraulics had functioned since 1948, and there was a substantial overlapping of personnel within the ASCE and Corps organizations. Fortson and Caldwell, for example, were members of the original five-man Executive Committee of the ASCE entity.

Professional activities of the Station's engineers transcended national boundaries. In the mid-1930s European hydraulic engineers, primarily German, founded the International Association for Hydraulic Structures Research. The title was later shortened to International Association for Hydraulic Research (IAHR). Attendance at its First International Congress in Berlin in 1937 reflected a Eurocentric focus, with only one American present. A second meeting, planned for Liege, Belgium, in 1939, was canceled due to the outbreak of war. Not until 1948 did the IAHR's Second International Congress convene in Stockholm, Sweden. It and subsequent meetings in Grenoble, Switzerland, and Bombay, India, in 1949 and 1951, respectively, gave indications of an increasingly global complexion, with American and French engineers in conspicuously important positions. The Fifth International Congress, held at Minneapolis in 1953, elected WES potamology and tidal hydraulics consultant Straub as president of its permanent International Committee. Tiffany also attended the Minnesota sessions, representing the Executive Committee of the ASCE Hydraulics

Division, while WES Hydraulic Analysis Branch Chief Campbell and former WES employee Caldwell presented papers.[42]

Brown served as the official representative of the Corps of Engineers and WES at the next scheduled IAHR Congress at The Hague, Netherlands, in 1955. He then toured hydraulics laboratories in Holland, France, and England. Among his observations was that the Laboratoire Dauphinois d'Hydraulique at Grenoble, France, was the largest and most advanced in Europe. Its library was singularly impressive, with practically all technical magazines and publications available (including Russian), all well catalogued and cross-indexed. The institute's director, Pierre Danel, had recently succeeded Straub as president of the IAHR International Committee. Still, Brown concluded, "at the risk of appearing prejudiced," that WES was equal or superior to any European hydraulic laboratory inspected.[43]

Campbell, following Brown's lead, represented WES at the Seventh IAHR Congress in Lisbon, Portugal, in 1957, before touring laboratories in Portugal, France, Italy, England, and Germany. His evaluations, like Brown's, reflected the broadened scope and acceptance of hydraulic modeling on an international level. In a telling comment, Campbell noted that German laboratories had engaged in relatively little activity since World War II. He also recognized the dominance of Danel's Grenoble facility in Europe, but opined that the volume of hydraulic laboratory work in the United States at the time exceeded that conducted in the rest of world combined. Yet less than 30 years had passed since Germany effectively monopolized hydraulic engineering or since the establishment of WES.[44]

WES remained active in international colloquia into the 1960s. Brown attended the IAHR's Ninth Congress at Dubrovnik, Yugoslavia, in 1961. Campbell participated in meetings of the International Organization for Standards in Paris in 1960, at New Delhi, India, in 1961, and in London in 1965. Both Brown and Campbell took further extensive tours of European laboratories in conjunction with professional meetings. In 1963 Fortson inspected English and French hydraulics facilities after serving on a military engineering panel in London. All were favorably impressed by the Wallingford Research Station on the Thames, whose director, Fergus Allen, had visited WES several times.[45]

In perhaps the most unusual excursion, Tiffany joined a small but prominent group of American engineers in touring parts of the Soviet Union. At Rouse's instigation, the U.S. State Department proposed an organized tour of Soviet facilities in 1960 but received no response from the Soviet Embassy in Washington. Rouse then persuaded the State Department to assist in arranging trips for interested parties on an individual basis through the Soviet Intourist Bureau. On 11 September 1961 four leading American engineers, Tiffany, Rouse, Straub, and Harold M. Martin of the Bureau of Reclamation's Hydraulic Laboratory at Denver, arrived in Moscow. Ippen joined the group four days later due to difficulties in obtaining a visa to enter the USSR from Yugoslavia. Despite the strains of the Cold War, the group met with considerable hospitality and goodwill, especially from its counterparts in the Soviet engineering and scientific community. Tours of hydraulics facilities in Moscow, Sochi, and Leningrad provided a rare view of engineering activities behind the Iron Curtain.[46] The timing of the trip was especially fortuitous in that the Cuban Missile Crisis erupted the following month.

Notes

1. An excellent brief discussion of estuaries is included in Frank A. Herrmann, Jr., "Estuaries," WES *Miscellaneous Paper H-72-4* (Vicksburg: WES, 1972). Herrmann first presented the paper at the American Society of Civil Engineers Georgia Section Meeting in Savannah, Georgia, in December 1971.

2. *Model Study of Saltwater Intrusion, Lower Mississippi River: Preliminary Report* (Vicksburg: WES, 1942). Also Frank A. Herrmann, Jr., and Joseph V. Letter, "Advances in Tidal Hydraulics," in Adnan M. Alsaffar, ed., *50th Anniversary of the Hydraulics Division, 1938-1988* (New York: American Society of Civil Engineers, 1988), 47-48.

3. Ibid.

4. See Morrough P. O'Brien and John Cherno, "Model Law for Motion of Saltwater Through Fresh," *Transactions of the American Society of Civil Engineers* 99 (1934): 576-94.

5. See, for example, Garbis H. Keulegan, "Third Progress Report on Model Laws for Density Currents for Chief of Engineers, U.S. Army," WES *Contract Report 2-1, No. 3* (Vicksburg: WES, 1946), 13.

6. Garbis H. Keulegan.......

7. In-depth biographical information on Keulegan is provided in John F. Kennedy, "Garbis H. Keulegan: A Physicist's Long Life in Hydraulics," American Society of Civil Engineers: Journal of Hydraulic Engineering 117 (1991) 12: 1575-587. Further personal information was provided by his daughter, Emma Pauline, interview by author, Vicksburg, 13 June 1996. Other sources include brief biographies produced by the WES Public Affairs Office, and a biographical sketch for his nomination to honorary membership in the American Society of Civil Engineers.

8. Rouse and Ince, *History of Hydraulics*, 181.

9. For example, Billy H. Johnson, interview by author, Vicksburg, 10 June 1996.

10. "Plans for Improvement of Navigation Conditions and Elimination of Shoaling in Savannah Harbor, Georgia, and Connecting Waterways, Model Investigation," WES *Technical Memorandum No. 2-268* 2 vols. (Vicksburg: WES, 1949).

11. A description and illustration of the improved tide producing machine is included in "Improvement of the St. Johns River, Jacksonville to the Atlantic Ocean," WES *Technical Memorandum No. 2-244* (Vicksburg: WES, 1947).

12. John B. Lockett, "History of the Corps of Engineers Committee on Tidal Hydraulics," Committee on Tidal Hydraulics *Technical Bulletin No. 16* (Vicksburg: MRC, 1972), iii-iv; also "Plans for Improvement of Navigation Conditions and Elimination of Shoaling in Savannah Harbor, Georgia, and Connecting Waterways," WES *Technical Memorandum No. 2-268* (Vicksburg: WES, 1949). Lockett's account differs somewhat from the WES version in *Technical Memorandum No. 2-268*. The WES publication states that the model was first filled with saltwater. Lockett was Recorder or the Corps' Committee on Tidal Hydraulics and prepared his history with the assistance and counsel of committee members. These included Simmons, who was the engineer in direct charge of the model.

13. Lockett, "History."

14. Ibid.

15. Ibid.

16. Henry B. Simmons, "Applicability of Hydraulic Model Studies to Tidal Problems," in *Committee on Tidal Hydraulics Report No. 1* (Vicksburg: MRC, 1950), 127-45.

17. For example, E. A. Schultz and Henry B. Simmons, "Freshwater-Saltwater Density Currents, A Major Cause of Siltation in Estuaries," Committee on Tidal Hydraulics *Technical Bulletin No. 2* (Vicksburg: MRC, 1957). Schultz and Simmons presented the paper in its year of publication at the XIXth International Navigation Congress in London.

18. "Delaware River Model Study Report No. 1: Hydraulic and Salinity Verification," WES *Technical Memorandum No. 2-337* (Vicksburg: WES, 1956); and Henry B. Simmons, "Use of Models in Resolving Tidal Problems," *American Society of Civil Engineers: Journal of the Hydraulics Division* 95 HY1 (1969): 125-46.

19. Ibid. A series of WES tests conducted in flumes from 1947-50 contributed to development of more accurate roughness standards. "Roughness Standards for Hydraulic Models Report No. 1: Study of Finite Boundary Roughness in Rectangular Flumes," WES *Technical Memorandum No. 2-364* (Vicksburg: WES, 1953).

20. "Investigation for Reduction of Maintenance Dredging in Charleston Harbor, South Carolina," WES *Technical Report No. 2-444* (Vicksburg: WES, 1957).

21. Hurricane surge studies include H.B. Simmons and Irby C. Tallant, "Effects on Lake Pontchartrain, La., of Hurricane Surge Control Structures and Mississippi River-Gulf Outlet Channel, Hydraulic Model Investigation," WES *Technical Report No. 2-636* (Vicksburg: WES, 1963); and H.B. Simmons, "Protection of Narragansett Bay from Hurricane Surges, Summary Report, Hydraulic Model Investigation," WES *Technical Report No. 2-662* (Vicksburg: WES, 1964).

22. "Dispersion of Effluent in Delaware River from New Jersey Zinc Company Plant, Hydraulic Model Investigation," WES *Technical Report No. 2-457* (Vicksburg: WES, 1957).

23. Ibid.

24. H.B. Simmons and W.H. Bobb, "Hudson River Channel, New York and New Jersey Plans to Reduce Shoaling in Hudson River Channels and Adjacent Pier Slips, Hydraulic Model Investigation," WES *Technical Report No. 2-694* (Vicksburg: WES, 1965).

25. Ibid. The comprehensive New York Harbor complex model has in previous works been confused with the earlier, smaller, East River model built for the Navy during World War II (Chapter 4). Cotton incorrectly uses a photograph of the comprehensive harbor model to depict the earlier effort. Pendergrass states that the earlier East River model was the same as that used in the later tests when, in fact, it was an entirely different model.

26. "Contamination Dispersion in Estuaries, New York Harbor, Hydraulic Model Investigation," WES *Miscellaneous Paper No. 2-332, Report 3* (Vicksburg: WES, 1961).

27. H.B. Simmons and W.H. Bobb, "Pollution Studies for Interstate Sanitation Commission, New York Harbor Model, Hydraulic Model Investigation," WES *Miscellaneous Paper No. 2-558* (Vicksburg: WES, 1963).

28. H.B. Simmons and W.H. Bobb, "Effects of Proposed Runway Extensions at LaGuardia Airport on Tides, Currents, Shoaling, and Dye Dispersion, Hydraulic Model Investigation," WES *Miscellaneous Paper No. 2-641* (Vicksburg: WES, 1964).

29. "Contamination Dispersion in Estuaries, Delaware River, Hydraulic Model Investigation," WES *Miscellaneous Paper No. 2-332, Report 1* (Vicksburg: WES, 1959); "Contamination Dispersion in Estuaries, Narragansett Bay, Hydraulic Model Investigation," WES *Miscellaneous Paper No. 2-332, Report 2* (Vicksburg: WES, 1959); and H.B. Simmons and W.H. Bobb, "Contamination Dispersion in Estuaries, San Francisco Bay, Hydraulic Model Investigation," WES *Miscellaneous Paper No. 2-332, Report 4* (Vicksburg: WES, 1962).

30. Hydrocomp, Inc., *Users Guide for the San Francisco Bay-Delta Tidal Hydraulics Model* (San Francisco: U.S. Department of the Army, Corps of Engineers, 1981), includes historical information on origins and construction of the model.

31. Simmons and Bobb, "San Francisco Bay, Hydraulic Model Investigation."

32. Tiffany, *History of WES*, VIII-1.

33. *Preliminary Report No. 1: Effects of Explosions in Shallow Water* (Vicksburg: WES, 1951).

34. The test series from 1951 to 1953 resulted in publication of nine unnumbered reports entitled *Effects of Explosions in Shallow Water*, and a summary as "Effects of Explosions in Shallow Water, Final Report," WES *Technical Memorandum No. 2-406* (Vicksburg: WES, 1955). All were confidential until the early 1960s.

35. A full discussion of instrumentation is included in *Effects of Explosions in Shallow Water, Report 9: Instrumentation* (Vicksburg: WES, 1953).

36. *Soils Conditions Beneath Coastal Harbors — United States* (Vicksburg: WES, 1952).

37. "Underwater Explosion Test, Sevier Bridge Reservoir, Utah," WES *Technical Memorandum No. 2-397* (Vicksburg: WES, 1955).

38. "Effects of Explosions in Deep Water, Final Report," WES *Technical Memorandum No. 2-427* (Vicksburg: WES, 1956).

39. See *Annual Summary of Investigations in Support of the Civil Works Program for Calendar Year 1960. Annual Summary No. 10* (Vicksburg: WES, 1961).

40. Ibid.

41. Ibid.

42. See *Proceedings: Minnesota International Hydraulics Convention. A Joint Meeting of International Association for Hydraulic Research and Hydraulics Division, American Society of Civil Engineers, University of Minnesota, Minneapolis, Minnesota, September 1-4, 1953* (Minneapolis: University of Minnesota, 1953).

43. See Frederick R. Brown, "Report on Attendance at Sixth Congress of International Association for Hydraulic Research, The Hague, Netherlands, 30 August — 6 September 1955, and Visits to Hydraulic Laboratories in France and England," WES *Miscellaneous Paper No. 2-164* (Vicksburg: WES, 1956).

44. Frank B. Campbell, "Report on Attendance at Seventh Congress of IAHR, Lisbon, Portugal, and Visits to Hydraulic Laboratories in Europe and England," WES *Miscellaneous Paper No. 2-239* (Vicksburg: WES, 1957).

45. Frederick R. Brown, "Report on Ninth Congress of International Association for Hydraulic Research, Dubrovnik, Yugoslavia, 3-7 September 1961, and Conference Excursion," WES *Miscellaneous Paper No. 2-522* (Vicksburg: WES, 1962); Frank B. Campbell, "Report on Attendance at International Organization for Standards Meeting, Paris, France, and Visits to Hydraulic Laboratories in Europe and England," WES *Miscellaneous Paper No. 2-401* (Vicksburg: WES, 1960); Frank B. Campbell, "Report on Attendance at International Organization for Standards Meeting, New Delhi, India, and Visits to Indian Hydraulic Laboratories," WES *Miscellaneous Paper No. 2-434* (Vicksburg: WES, 1961); Frank B. Campbell, "Report on Attendance at International Standards Organization Technical Committee Meeting, London, 1965, and Hydraulics Laboratory Visits," WES *Miscellaneous Paper No. 2-734* (Vicksburg: WES, 1965); and Eugene P. Fortson, "Visits to Hydraulic Laboratories in England and France, March 1963," WES *Miscellaneous Paper No. 2-578* (Vicksburg: WES, 1963).

46. A fascinating account of conditions in the Soviet Union and of the condition of Soviet hydraulics facilities is contained in Joseph B. Tiffany, "Exchange Visit of U.S. Hydraulic Laboratory Directors to USSR, September 1961," WES *Miscellaneous Paper No. 2-464* (Vicksburg: WES, 1961).

7 The Computer Revolution, 1963-1983, Part I: Estuaries and Wave Dynamics

Organizational and Administrative Change

Despite revolutionary upheavals wrought by computerization and the environmentalist movement between 1963 and 1983, the administrative structure of the Hydraulics Division and its successor in title, the Hydraulics Laboratory (HL), remained stable. Significant (and sometimes confusing) changes in terminology occurred in 1972 when the Corps upgraded all of the Station's divisions — Hydraulics, Soils and Pavements, Concrete, Weapons Effects, Mobility and Environmental, and Explosive Excavation Research — to laboratories. Thus the Hydraulics Division became the Hydraulics Laboratory. Primary research units within the laboratories, previously called branches, then became divisions.

Changes in terminology and status had little effect on the Hydraulics Division/Laboratory's internal structure. Through most of the period under consideration it retained the five sub-units (branches/divisions) dating from the 1950s:

- Estuaries,
- Hydraulic Analysis,
- Hydraulic Structures,
- Water Waves (Wave Dynamics after 1969), and
- Waterways.

For several years during the 1970s the Mathematical Hydraulics Group joined the other five with branch, then division status, before merging into the Waterways Division.

Structural stability withstood a number of personnel changes. Fortson retired as Division Chief in 1970 after a remarkable WES career. With the exception of stints on active duty with the Army in World War II and the Korean conflict, he had served as Hydraulics Division Chief for nearly 30 years. Henry Simmons, long-time Estuaries Branch head, succeeded Fortson. Frank A. Herrmann followed Simmons over the Estuaries Branch. When Herrmann rose to become Simmons' Assistant Laboratory Chief in 1974, Richard A. Sager succeeded Herrmann as Estuaries Branch Chief. Among other


Henry B. Simmons


Frank A. Herrmann

Richard A. Sager

Ellis B. Pickett

changes, Ellis B. Pickett replaced Frank Campbell as head of the Hydraulic Analysis Branch in 1968, Robert W. Whalin succeeded Robert Hudson as Wave Dynamics Branch Chief in 1971, John L. Grace assumed leadership of the Structures Division at the retirement of Thomas Murphy in 1973, and J.E. Glover took over the Waterways Division from Franco in the same year. (See Appendix A: Organization Charts.)

At a higher administrative level, after 28 years as WES Technical Director, Joseph Tiffany retired in late 1968. The following spring, Fred Brown, a WES employee since 1934 and Assistant Technical Director since 1964, succeeded Tiffany. Brown held the post until 1985, so the Station had only two technical directors over a 45 year span. Both Tiffany and Brown had been instrumental in the establishment of WES as a world-renowned hydraulics research facility.

WES Enters the Computer Age

By the mid-1960s, while large-scale physical modeling of hydraulic prototypes reached its apex, a new and revolutionary tool began to alter research efforts: the electronic computer. The computer's influence had not been immediate. Since the early 1950s the Corps of Engineers had been aware of the increasing use of computers in its areas of engineering concern. In possibly the Corps' first attempt to apply computer methods to hydraulics-related field problems, in 1953 the Ohio River Division acquired a GEDA analog computer and contracted J.J. Stoker of New York University to a develop a program for the study of flood routing phenomena.[1] (Stoker's "explicit finite difference" scheme found use in many later computer models of unsteady flows in open channels.) By 1954 the Missouri River Division also began to apply computer programs to problems of reservoir releases and power distribution. Both divisions' efforts were incorporated into a formal Civil Works Investigation supervised by OCE.[2]

WES tentatively entered the computer age at about the same time. Anticipating the potential use of computers in hydraulic modeling, OCE in April 1954 requested that the Mississippi Basin Model Board consider the application of "high-speed electronic computer techniques to flood routing and other problems."[3] Modification, operation, and maintenance of the huge MBM was time consuming, expensive, and technically difficult, and serious questions existed as to its long-term potential and effectiveness. Computer applications could speed up its operations, make them more cost effective, and might even make further MBM construction unnecessary. Still, the OCE request noted that "It is not considered that electronic computers as such will ever be an alternate or substitute for hydraulic models except in special cases," and that "The computer is merely a means of solving more readily analytical problems that might otherwise be too laborious on account of the volume of computations."[4]

The MBM Board requested assistance from WES. Because in-house expertise was almost totally lacking, WES appealed to its hydraulics consultants; but among them, too, the new technology was not clearly understood. Ippen at MIT, for instance, emphasized the capability of physical models to respond dynamically to a sequence of hydraulic events, stating that "I fail to see how an electronic computer can be set up to do the same and how it can reproduce a correctly integrated history of many such interactions." Although claiming no special knowledge relating to computers, he and others felt the purposes for which the MBM was being built could be fulfilled only by a complex physical model.[5] The debate over the use or substitution of computers in the operation of the MBM remained temporarily unresolved. This was only the prelude to a lengthy battle between supporters of physical models and advocates of computerized numerical modeling.

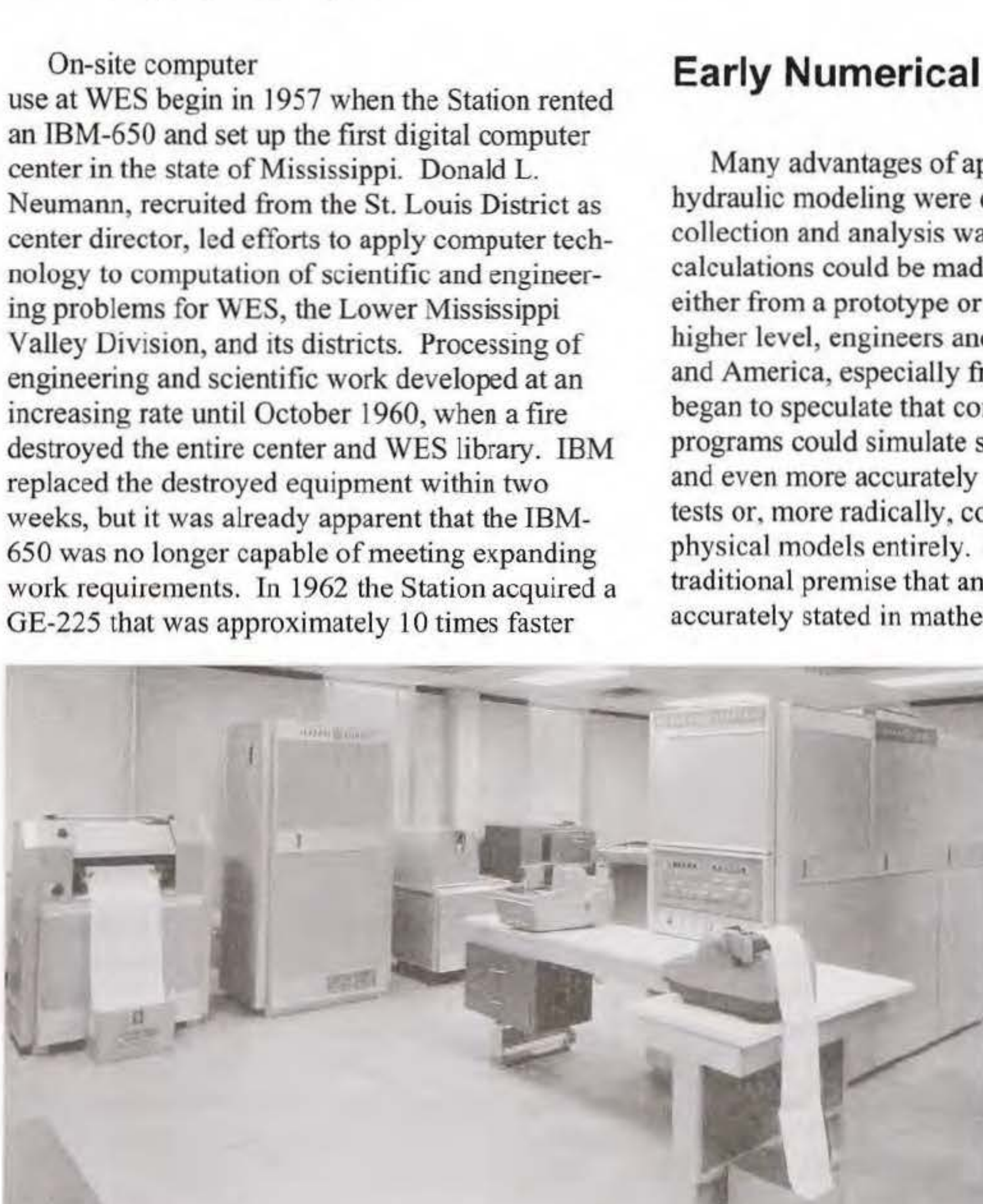
First WES computer, an IBM-650, 1957

than its predecessor. By 1966 the addition of six low-density tape drives further increased the computer's capabilities, while the computer center's staff grew to about twenty-five. In 1968 work requirements for ordinary problems made a 24-hours-per-day, 7-days-a-week operating schedule necessary, and larger problems that exceeded the WES computer's capacities were being processed by machines at other locations.[6] In the meantime, the use of computers had begun to challenge the very foundations of conventional hydraulic modeling.

On-site computer use at WES begin in 1957 when the Station rented an IBM-650 and set up the first digital computer center in the state of Mississippi. Donald L. Neumann, recruited from the St. Louis District as center director, led efforts to apply computer technology to computation of scientific and engineering problems for WES, the Lower Mississippi Valley Division, and its districts. Processing of engineering and scientific work developed at an increasing rate until October 1960, when a fire destroyed the entire center and WES library. IBM replaced the destroyed equipment within two weeks, but it was already apparent that the IBM-650 was no longer capable of meeting expanding work requirements. In 1962 the Station acquired a GE-225 that was approximately 10 times faster

Early Numerical Modeling

Many advantages of applying computers to hydraulic modeling were obvious: speedier data collection and analysis was possible, and complex calculations could be made rapidly using data either from a prototype or a physical model. On a higher level, engineers and scientists in Europe and America, especially from the academic world, began to speculate that computerized mathematical programs could simulate some phenomena faster and even more accurately than physical model tests or, more radically, could eventually replace physical models entirely. This was based on the traditional premise that any problem that could be accurately stated in mathematical form could be solved numerically. The advent of high-speed computers with large memory banks capable of accurately stating the extremely complex phenomena found in hydraulic prototypes, and the ability of computers to solve those problems, seemed to give computer modeling unlimited potential. Such computer models, usually called numerical or mathematical models, would



GE-225 computer, 1966

Naragansett Bay model (this study was one of the first to incorporate numerical modeling)

be cheaper, since it would not be necessary to construct, instrument, and man physical models. Numerical models could also provide much faster results than waiting for the outcome of lengthy physical model tests.

WES engineers first applied numerical modeling in projects dealing with Narragansett Bay. At the behest of the New England Division, from 1956 to 1963 the Station conducted a series of tests using a comprehensive physical model of the area. First efforts concentrated on evaluating structures to protect the bay from hurricane surges. The bay area was particularly susceptible to loss of life and property damage when hurricane-generated surges coincided with high water of normal tides, as had happened in 1938 and in 1954.[7] Protective measures had more than a provincial significance, as the bay was the location of a major Navy base and exclusive yacht clubs, one of which claimed John F. Kennedy as a member.[8]

Model reproduction of tides and currents in Narragansett Bay was not difficult, but reproduction of winds causing a hurricane surge presented special problems. Using conventional methods, Station engineers would have to design, construct, and operate expensive wind generating equipment and place the entire model inside a wind tunnel. However, lengthy discussions between WES and New England Division personnel led to a time-and-money saving alternative. Convinced that the New England Division could analytically determine local wind conditions and provide computerized data, WES confined its tests to normal gravitational tide phenomena. Computerized wind data was then factored into physical test data to provide adjusted results.[9]

A similar test series, conducted from 1965 to 1967, involved evaluation of hurricane barriers in Galveston Bay. Citing the successful application of analytical wind data from the New England Division in the Narragansett Bay tests, WES engineers again relied on a computerized wind program. Robert O. Reid of Texas A&M University and personnel of the Galveston District developed a digital computer program that separated the bay complex, including an adequate amount of the Gulf of Mexico, into a grid of

squares. Flow could be routed from square to square on the computer when the topography, average wave height, wind, and other empirical factors were known. Engineers could then predict water-surface elevations for desired locations in the bay for any surge in the Gulf of Mexico and any wind over the bay.[10] One disadvantage of the Galveston Bay mathematical scheme was that computations on the Galveston District's computer, a GE-225 with a mere 8K of memory, were costly and time consuming. Solution time for a typical problem was estimated to be 15 hours.[11]

Not all activities related to the Houston/ Galveston Bay area involved high technology. The routine of model testing was shattered early one morning when, in the physical model hanger at the Station, a lab technician got into a pickup truck to move it to the outdoor parking lot. Looking toward the passenger seat, he found himself face to face with a large and very unhappy monkey. Both driver and passenger raised blood-curdling screams and exited in opposite directions. Much of the morning was spent keeping the monkey at bay (pun intended) until it was captured. It had apparently escaped from a Vicksburg home where it was kept as a pet. Unfortunately, no one thought of photographing the beast, a la King Kong, with the physical model.

Changing the Guard

The computer revolution was often, with notable exceptions, a generational battleground. The pioneers of American hydraulic engineering — the generation that had led the United States to primacy in international engineering circles — were in many cases understandably reluctant to embrace unproven methods or tools. This was especially true of tools entailing byzantine complexities and embracing a new and esoteric vocabulary. As often transpires, many who had challenged the engineering status quo of the 1930s and 1940s were ill-equipped to face the new challenges of the 1960s and 1970s. For some the computer loomed as the harbinger of a new engineering age in which they perhaps no longer quite fit.

During the late 1950s and 1960s, WES began to experience a changing of the guard. At least one Station Director, Colonel C.H. Dunn, predicted the transformation. In 1954 Dunn noted in a letter to Ippen at MIT that WES had a critical need for at least 20 new engineers. Efforts to recruit young engineers had been unsuccessful because of competition from private industry. Although WES was a relatively young institution, most of its professional grade employees were in the same age group, about 45 years old, and most would be retiring within fifteen years. This made long-range planning impossible,[12] and would create a long-term problem if promising young engineers were not groomed to replace them. The younger additions of the late 1950s, 1960s, and 1970s were to spearhead a movement toward converting the Station to the new technology.

One of the relatively few new hires in the mid-1950s, at the dawn of the computer age, was Marden B. "Burt" Boyd, a Mississippi State College (now Mississippi State University) engineering graduate who took a position at WES in 1956. Boyd first worked in the Hydraulic Analysis Branch under Campbell before rising to the position of Section Chief in Murphy's Structures Branch. There Murphy and Boyd, possibly for the first time, used computers to calculate lock filling characteristics as part of the WES lock design program. In 1967 Boyd earned a graduate degree from Colorado State University, specializing in hydraulics and mathematics.[13] This reflected the Station's efforts by the mid-1960s to provide advanced educational opportunities and training for its employees, an effort that continues through the present.

Marden B. "Burt" Boyd

Boyd became an early and avid proponent of computerization. Upon his return to WES in 1967, he prompted the Hydraulics Division to make a stronger commitment in that area. Consequently, in September of that year the division initiated an

education program intended to improve and promote its computer capabilities. Boyd directed the effort, in addition to performing his regular duties. He first reviewed literature for computer methods that might be adapted to WES experiments, then assisted division personnel who had minimal (or no) exposure to computers in developing expertise.[14] Support arrived in January 1968 with the assignment of Captain John H. Harrison to the Hydraulics Division and the hiring of Larry L. Daggett. Both had recently earned doctoral degrees, Harrison from Virginia Polytechnic Institute and Daggett from Arizona State University. Boyd, Harrison, Daggett, and Garbis Keulegan then systematically attempted to recruit more personnel experienced in computer usage and numerical analysis. Ironically, Keulegan did not like calculators — much less computers — and preferred to work with an oversize slide rule.[15]

In January 1968, only four months after initiation of the computer education program, Boyd reported to a meeting of the WES Board of Hydraulics Consultants that division personnel were using computers for analytical studies that included refraction of Tsunami waves over long reaches of ocean, computation of wave characteristics along a canal connecting two reservoirs, and computation of lock filling characteristics. Computers were also used to process some model and prototype data. Keulegan, despite his personal aversion to the new machines, stated his conviction to the board that "The use of the computer is believed very necessary to the development of the whole Hydraulics Division," and that "individuals from each Branch [should] become completely conversant with the computer." Ippen, who had expressed strong reservations about computer capabilities for the MBM 14 years earlier, now in his role as a WES consultant added, "The importance of building up a staff competent in computer applications...should be emphasized." He further stated, "New staff members should be trained in programming and problem-solving by computers."[16] The revolution was gaining converts.

Mathematical Hydraulics Group

In 1968 in a major commitment to computerization and to the application of computers to modeling, Simmons established the Mathematical Hydraulics Group (MHG) as a special unit within the Hydraulics Division. Simmons, too, was a slow convert to computerization, admitting later that he was "one of the worst doubters they had," and that although he had 30 years of experience with physical models, he did not know "a damn thing about ...numerical models." To his credit, Simmons foresaw the coming computer revolution and put aside prejudices. He decided to form a small nucleus of individuals interested in computer modeling to review literature, talk to experts, assist personnel with computer-applicable problems, provide instruction in the use of computers and of time-sharing remote terminals, and begin developing programs for WES use.[17]

Keulegan supervised the group, which at first consisted of only four engineers: Boyd, Harrison, Daggett, and Lieutenant John F. Abel. By the end of 1968 the MHG was involved in a number of projects including:

- developing programs in conjunction with the Mississippi Basin Model to computerize flood routing techniques so that the MBM could be phased out of operation,
- experimental studies to determine the effects of viscosity and surface tension on vortices,
- writing a paper on the state of the art on artificial friction attenuation in wave models,
- developing computer programs to predict harbor oscillations, and
- developing automated data acquisition and processing capabilities for the entire Hydraulics Division.[18]

MHG projects by 1970 had grown to further encompass:

- prediction of oil slick behavior,
- computer analysis of unsteady flows in open channels,
- mathematical modeling of estuaries,
- comparison of mathematical and physical models for harbor oscillations, and

- development of a computer program to predict ship transit capacities of sea-level canals.

Largely through the efforts of the MHG, computerization began to influence the activities of the entire Hydraulics Division. The Hydraulic Analysis Branch, for example, as part of an OCE-sponsored Engineer Study (ES 804) shifted much of its energy towards the development of comprehensive computerized design criteria rather than site-specific standards.[19] In another project starting in 1970, the Estuaries Branch developed a computer system to automatically operate the existing New York Harbor model while measuring tide heights, currents, salinities, and temperatures.[20]

Chesapeake Bay: Pollution and Politics

A number of model projects in the 1970s illustrated the dissension between physical and numerical modeling proponents and their attempts to arrive at a reasonable synthesis. The largest of these efforts, construction of a costly and controversial model of Chesapeake Bay, represented the last attempt at large-scale physical estuary modeling by the Corps without first considering computer applications and the potential for numerical modeling. The planning, design, construction, verification, and operation of the model, in fact, spanned the period in which computers revolutionized hydraulic modeling. And unfortunately for critics of numerical modeling, the project pushed physical modeling beyond the limits of effectiveness in both technical and economic terms.

Chesapeake Bay is the largest tidal estuary in the United States and one of the largest and most important in the world. It stretches almost 200 miles from the mouth of the Susquehanna River south to the Virginia capes at Norfolk. Varying from 4 to 30 miles in width, it has a jagged shoreline of more than 4,300 miles, and is fed by nearly a dozen major rivers and three dozen lesser ones. Its size and multitude of freshwater sources, coupled with complex tidal and salinity factors, make the Chesapeake exceptionally difficult to model and analyze.

By the 1960s Chesapeake Bay faced numerous problems typical of modern estuaries. Dredged materials, when dumped overboard, often returned to channels, compounding maintenance problems and increasing costs. Remaining materials created turbidity and interrupted biological processes. Enlarged navigation channels led to further salt-water intrusion in numerous inlets and rivers, while attendant increases and shifts in shoaling created commercial and environmental obstacles. With commercial and residential development, shoreline erosion worsened. Most serious of the bay's problems, however, were the huge discharges of human and chemical wastes into the estuary and the unrestricted dumping of heated water by power plants.

Although continued development threatened the entire biological and commercial future of the bay and its surrounding wetlands, concerted action was slow to develop. Finally, in its River and Harbor Act of 1965 Congress authorized the Chief of Engineers to make a complete investigation of water utilization in Chesapeake Bay. The enabling legislation also directed the Corps to "construct, operate, and maintain in the State of Maryland a hydraulic model of the Chesapeake Bay Basin." The decision to locate the model in Maryland was the product of a concerted lobbying effort by the Maryland congressional delegation and was intended to take advantage of intense local enthusiasm for the project.[21]

As a policy-making agency, the North Atlantic Division established the Chesapeake Bay Study Advisory Group, but actual administration of the model study fell to the Baltimore District. In 1967 the State of Maryland, through Governor Spiro Agnew, provided a 65-acre plot near Matapeake for the model site. In a puzzling gesture, Maryland supporters of the project claimed to have favored Matapeake because its weather conditions were exactly like those of Vicksburg.[22] The following year the Baltimore District contracted with WES to design and build a huge physical model of Chesapeake Bay at the Matapeake site, while a private construction firm was to design and manufacture a model shelter.[23]

Although the model was to be designed at the Station, its construction at a remote site prompted grave concerns. Henry Simmons led arguments that it should be built at WES to provide maximum efficiency. Noting that escalating costs at the San Francisco Bay model were largely due to the necessity of hiring additional administrative and technical staff, he pointed out that these costs would not be incurred in Vicksburg and that skilled, experienced crews were available there for construction. Due to political considerations, the warnings of Simmons and others went unheeded.[24]

Physical versus Numerical Modelers

The Chesapeake Bay model aroused controversies that far transcended the issue of site selection. As early as 1967 scientists and engineers debated the feasibility of using numerical models rather than a physical model to study the Bay. The academic community tended to strongly favor the numerical approach except for some consultants who, often through ties with WES, were familiar with the capabilities of physical models. Professors Myron B. Fiering and long-time Corps critic Arthur Maass of Harvard University, for example, chastised the Corps for remaining wedded to outmoded procedures in its plans for the Chesapeake model, and numerical modeling proponent William Hargis of Virginia openly questioned the need for a physical model of the enormous estuary at the first meeting of the Chesapeake Bay Study Advisory Group.[25] Defending the need for a physical model, more traditional engineers such as Ippen of MIT and Clarence Wicker, formerly of the Philadelphia District and a founder of the Corps' Committee on Tidal Hydraulics, believed that computers were valuable tools, but that computer models were inferior to physical models. No computer, in their estimation, could handle the approximately 20,000 grid points that a Chesapeake Bay study would require.

By the late 1960s, while the Chesapeake Bay project was in abeyance, debate within the Corps over computerization grew particularly heated in the Committee on Tidal Hydraulics. In 1969 Committee Recorder John B. Lockett criticized Professor Frank D. Masch of the University of Texas for overrating the ability of numerical models to simulate estuary phenomena. In a lengthy response, Masch emphasized that he was not from the "old school" like Ippen, Pritchard, Wicker, and Keulegan, but was a convert to the potential of computer modeling. "I think," he said, "the day is coming, and sooner than many people think, when physical models will be outmoded."[26]

Typically cautious, in 1969 the Committee rejected an offer by MIT to develop a numerical model of Upper Chesapeake Bay, but set aside $50,000 annually for the WES Mathematical Hydraulics Group to conduct research. Tiffany, who had retired as WES Technical Director at the end of 1968 but was still a member of the Committee on Tidal Hydraulics, then urged OCE to allow the MHG rather than MIT to pursue development of an Upper Chesapeake Bay numerical model. The MHG, according to Tiffany, "had more intelligence" than the MIT group, worked in a real laboratory, and had ready access to the expertise of Henry Simmons and other estuary modeling pioneers. Tiffany also encouraged OCE to develop an in-house Corps computer modeling capability rather than cooperate closely with academic centers. Although Tiffany apparently intended to ensure that WES would remain preeminent in physical hydraulic modeling and would be able to develop a numerical modeling capability if needed, this had the unfortunate effect of temporarily isolating WES from developments in the academic community.[27]

Aerial view, Chesapeake Bay model facility

Chesapeake Bay Model: Design, Construction, Verification

As the debate between physical and numerical modelers unfolded, WES began design of the Chesapeake Bay model in March 1967. Blueprints called for by far the largest indoor model ever built, spanning approximately 8.6 acres, or 327,000 square feet. In comparison, the existing WES New York Harbor model covered 24,000 square feet and the Delaware River estuary model about 30,000 square feet; the largest estuary model at the Station was the Galveston Bay/ Houston Ship Channel at 57,000 square feet. Even the giant San Francisco Bay model was only half the planned length of its East Coast counterpart. A model shelter, also in the design stage, was to be 40 feet tall, 1,080 feet long, and 680 feet wide, enclosing an area of over 14.5 acres.[28]

By 1968 WES had made significant progress in model planning, including design of high-precision water level measuring instruments. However, Federal budget cuts for Fiscal Year 1969 resulted in the first of a series of delays that resulted in the suspension of activities for several years. Whereas the Baltimore District, in an

Chesapeake Bay model

overly optimistic projection, had hoped to finish model construction by September 1970, ground-breaking activities did not take place until June 1973. Crews installed concrete molding of bathymetry between February 1975 and February 1976, and verification studies lasted from April 1976 until December 1977. Thirteen years after its enabling legislation, the model was ready for operation in July 1978.[29] In the meantime, although unverified and far from practical use, in 1976 the National Society of Professional Engineers named it one of the 10 outstanding engineering achievements of the year.

As Simmons had warned, building at the Maryland site posed chronic administrative and technical hardships for WES employees. Shortly after construction began the Hydraulics Laboratory established a separate Chesapeake Bay Model Branch within Sager's Estuaries Division to direct the project. Three engineers — T. Hill, D.F. Bastian, and R.O. Bruno — served as chiefs. The branch formed the nucleus of a permanent on-site WES staff that supervised construction and ensured the model conformed to WES standards. Sager commuted to Maryland every weekend for six months.[30] Because it was impossible to use experienced WES construction personnel for the duration of the project, a cadre of WES workmen and technicians also moved temporarily to Matapeake, began building the model, and simultaneously trained three crews (12 to 15 men each) of local workers. After construction, another 11-man WES team spent several months verifying the model.[31]

Due to its unprecedented size, the model was singularly difficult to verify and operate. However, installation of a WES-developed computer control and monitoring system greatly enhanced performance. By the mid-1970s, while the Chesapeake Bay model was under construction, WES had installed a computer control system in its existing New York Harbor model and had incorporated a much more successful automated system into its Los Angeles/Long Beach Harbor model. Station engineers then adapted the Los Angeles/Long Beach Harbor system for use in the Chesapeake Bay model by developing instrumentation specifically for the larger model.[32]


Chesapeake Bay model automated control center

Further complications derived from the enormous amount of prototype data needed from the bay for the model to reproduce. With its myriad of freshwater sources, tidal surges, salt water intrusion, pollution, traffic, commercial development, wind contamination, and other phenomena, the Chesapeake was uncommonly resistant to quantification. In fact, the lack of comprehensive data from the bay made conventional verification procedures impossible. The WES verification team nonetheless concluded in its final report that the model was "well verified" and could be used as "the predictive tool it was designed to be."[33] The Baltimore District, in a subsequent *News Circular*, confidently noted that verification was "a most significant milestone," and that "at long last, a scientific instrument is available which reduces to a manageable scale that complex estuary known as Chesapeake Bay."[34]

Chesapeake Bay Model Closes

Between 1978 and 1980 several successful studies were completed for the Baltimore District using the supermodel. These included evaluating a proposed project for deepening Baltimore Harbor and its channels, testing Chesapeake Bay for sensitivity to salinity changes caused by flows from the Chesapeake and Delaware Canal, and devising efficient water supply and wastewater disposal programs for the Potomac Estuary.[35] However, while second-phase testing of the Potomac Estuary was in progress in the spring of 1980, operators became aware that the model could not duplicate results obtained in first-phase testing the year before. Concrete expansion had compressed some of the model's joints, causing the edges of whole

slabs to heave and buckle. A detailed survey indicated that at least 10 percent of the model had suffered sufficient concrete movement to produce questionable test results. Over a period of months, WES engineers supervised the remolding of about 23,000 square feet of concrete and the widening and filling of all existing expansion joints, complete with plastic expansion gages.[36]

Despite repairs and reverification, the Chesapeake Bay model was near the end of its useful life. Congress did not fund further studies and other potential sponsors could not (or would not) bear the expense of model use. Costs of operating the facility had reached $4,000 per day by 1980, compared to about $1,000 per day for most other estuary models. But more importantly, the model was a victim of the computer revolution sweeping through hydraulic engineering at the time. By the end of 1981, as work on the Chesapeake model came to a halt, clients preferred or even insisted on computer-based numerical estuary models, believing them to be cheaper and, in many areas, more accurate than their physical counterparts.

Chesapeake Bay Model Highlights

Model Area: Approximately 8.6 Acres
Shelter Area: Approximately 14 Acres
Shelter Length: 1,080 Feet
Shelter Width: 680 Feet
Shelter Height: 40 Feet
Required Masonite Templates: 26 Miles
Metal Roughness Strips: 700,000
Maximum Model Water Depth: 21 Inches
Average Model Water Depth: 3 Inches
Volume of Water in Model at Mean Low Water: 450,000 Gallons
Appurtenances:
- 2 Tide Generators
- 25 Electronic Water Surface Gages
- 75 Point Gages
- 2 Water Pumps with 1.25 Million Gallon Capacity
- 2 Microcomputers

Cost: About $30 Million
Water Usage: About 1 Million Gallons Per Day
Salt Usage: About 20 Tons Per Day

Hybrid Estuary Modeling

During much of the Chesapeake Bay model's turbulent history, a group of younger WES engineers led a movement, ultimately a crusade, within the Hydraulics Division toward computer modeling of estuaries. One was William H. McAnally, a native of Florida who took a job with Fred Brown's Nuclear Weapons Effects Division after graduating from Arizona State University in 1969. His work with computers at WES began immediately only because he had fortuitously taken a FORTRAN course during his senior year.[37]

William H. McAnally

In 1971 McAnally moved to the Hydraulics Division's Estuaries Branch. There he at first found a degree of insularity among some members of the staff. Experienced physical modelers, known worldwide for pioneering efforts in their field, resented criticism, especially from "ivory tower" academicians and "young whippersnappers" who leaned toward numerical modeling. Despite earlier reports from the Mathematical Hydraulics Group to the WES Board of Hydraulics Consultants that computer usage within the Hydraulics Division was burgeoning, McAnally found that he was the only person in the Estuaries Branch doing computer programming.[38]

Influenced by scholarly publications, professional conferences, and work on the Chesapeake and Delaware Canal and the New York Harbor models, McAnally became convinced that computer modeling was the wave of the future. He also recognized the need for advanced education, so from 1972 to 1973 earned a master's degree from the University of Florida through WES's program of ongoing graduate training. At Florida, McAnally was strongly influenced by Professor Emmanuel Partheniades. Partheniades had quite an academic pedigree, having studied as an undergraduate at MIT under Ippen before earning a doctorate under Hans Einstein from the University of California at

Berkeley. At Partheniades' suggestion, McAnally began to explore the potential of hybrid modeling.[39]

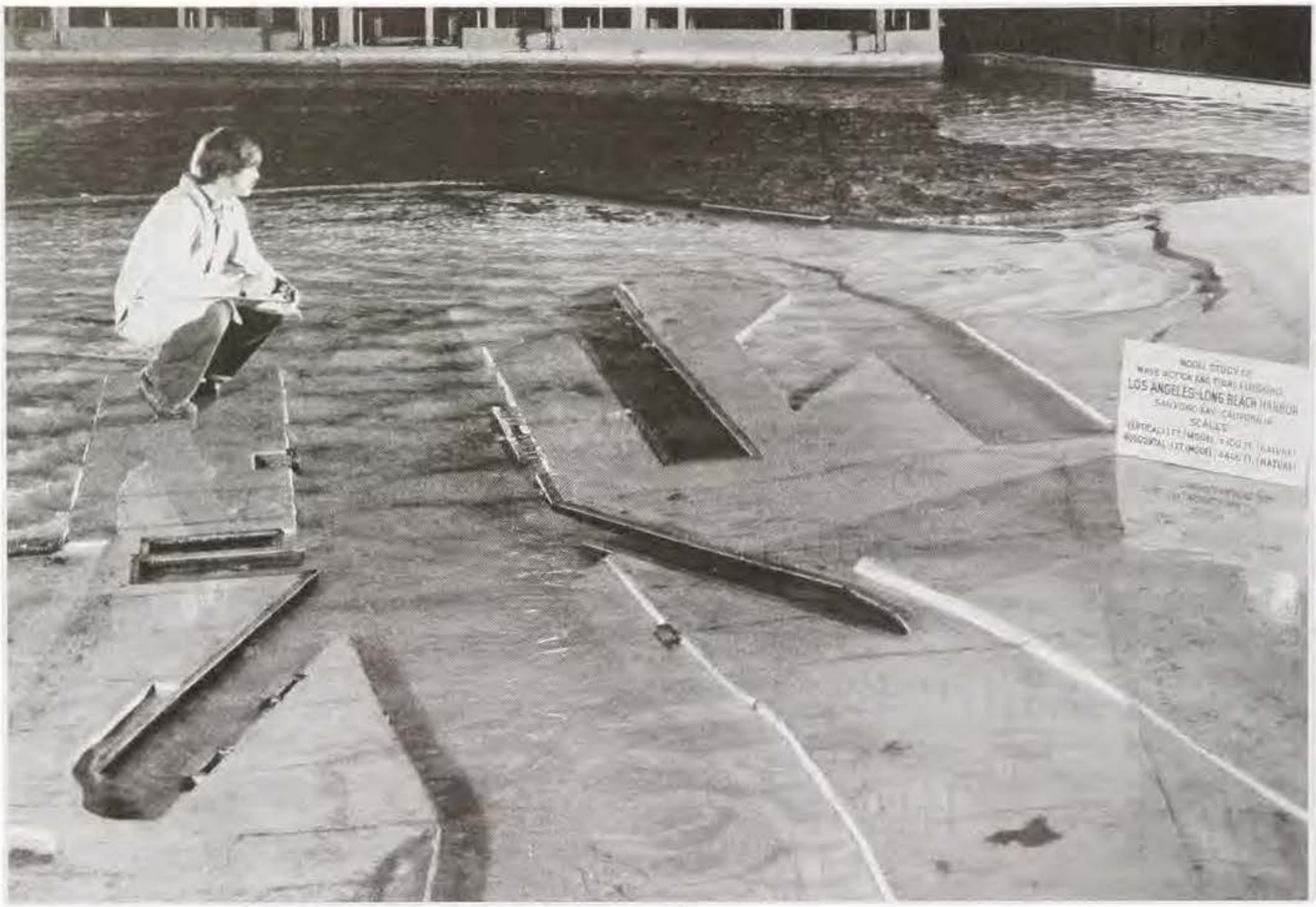
Solutions to coastal or any other hydraulics problems could be obtained by use of four primary methods — field observations, analytical solutions, numerical models, and physical models. Any of the four could be the best approach for solving a specific problem, and each had fundamental strengths and weaknesses. In practice, two or more methods were often combined in simple ways, with each method applied to the portion of a problem to which it was best suited. By the 1970s sufficient experience with physical models and the development of computer programs enabled engineers to combine numerical and physical models in ways not hitherto possible. Such combinations were called hybrid models. Combining numerical and physical models in closely coupled fashions that permitted feedback between the two models was called integrated hybrid modeling. Estuaries provided good candidates for hybrid modeling because, among other reasons, while physical models could accurately simulate currents and water levels, they often gave poor simulations of sediment transport and deposition. Numerical models, on the other hand, could be developed to predict such phenomena as sedimentation and wind effects. The integration of the two could provide engineers with solutions not attainable by use of any single method or model.[40]

McAnally's studies at the University of Florida convinced him that integrated hybrid modeling could succeed and that, indeed, it would make pure physical modeling obsolete. By the mid-1970s he believed that even hybrid modeling would be only a transitional method leading to the complete acceptance of numerical modeling at the expense of physical modeling.[41] These ideas gained further support at WES with the continuing influx of more engineers of the computer generation. W. A. "Tony" Thomas, whom Simmons enticed from the Corps' Hydrologic Engineering Center (HEC) in California to join the Mathematical Hydraulics Group; Billy H. Johnson, hired by Boyd after he received a Ph.D. from Mississippi State University in 1971; Donald C. Raney, who came to WES from the University of Alabama under an Intergovernmental Personnel Agreement, and others were to form partnerships that eventually led to the development of computer programs revolutionizing numerical estuary modeling and placing WES at the forefront of the new technology.

As early as March 1974, an interdisciplinary WES team that included McAnally, Raney, Hudson, and Joe V. Letter, recommended a hybrid approach in a study for the Pacific Ocean Division. Reporting on conditions at Kaneohe Bay, Hawaii, the WES group noted that the bay system was so complex that both physical and numerical models would be needed for a full study. McAnally stated that "Only the physical model can incorporate the effects of wind waves and stratification, whereas water-surface setup and currents induced by wind can only be included in the numerical model." To promote the advantages of hybrid modeling, he further avowed that the two techniques — physical and numerical modeling — were "complementary rather than competitive."[42]

Transition: Los Angeles/Long Beach Harbor Study

The first large-scale WES project to incorporate hybrid modeling from its inception was a study of the Los Angeles/Long Beach Harbor complex requested by the Los Angeles District. Due to growing demands for ship mooring facilities, the Los Angeles and Long Beach Port Authorities planned to construct additional harbor basins and dredge deeper channels in existing harbor areas. Such a project, which would take 10 to 15 years to complete, involved consideration of a plethora of factors typical to large, complex harbors. These included tidal computations, wave oscillations, ship movements, wind effects, littoral currents, and sedimentation. To facilitate efforts, Congress empowered the Chief of Engineers to order whatever model tests were deemed necessary; OCE assigned the task to WES.[43] This led to construction of the Station's first completely automated physical model.



Los Angeles/Long Beach Harbor model – transition to "hybrid" modeling

After a lengthy period of data acquisition from the harbor complex, WES completed construction and verification of a 44,000-square-foot physical model in 1975.[44] The great complexity, large size, and anticipated volume of data the model would produce forced designers to abandon conventional techniques. Manual procedures for collecting and analyzing model wave data alone would have required approximately seven man-years of labor. In defining a new state of the art for physical estuary models, WES engineers devised a comprehensive, computerized "Automated Data Acquisition and Control System" (ADACS), complete with supporting software, to operate the model and to record and evaluate data. Except for wave sensors and wave generator units, all components of ADACS were housed in a trailer adjoining the model.[45]

While the physical model produced voluminous data, WES developed numerical models of some aspects of the prototype's behavior. Raney, with support from McAnally and Robert W. Whalin's Wave Dynamics Division, devised a two-dimensional hydrodynamic model based on a Rand Corporation program to numerically investigate tidal circulation in existing basins and to define and evaluate the impact of certain proposed modifications.[46] James R. Houston, also of the Wave Dynamics Division, adapted a computer program developed at MIT by H.S. Chen and C.C. Mei to calculate harbor oscillations. Both efforts produced good agreement between prototype measurements in the harbor complex and the numerical models.[47]

WES numerical modelers on the Los Angeles/ Long Beach project became painfully aware of a glaring deficiency: the Station's in-house computer capability was completely outdated. Although the WES Automatic Data Processing Center had acquired a $2 million Honeywell G-635 computing system in 1973 and operated it on an almost continuous basis, demand far exceeded capacity. McAnally, Raney, Houston, and others had to travel regularly to the Army's Redstone Arsenal at Huntsville, Alabama, or to the Los Alamos Scientific Laboratory, New Mexico,

where adequate computer capabilities were available. Even then, WES engineers, punch cards in hand, were often at the mercy of other users and had to settle for whatever times were open. Working almost non-stop through weekends was typical. McAnally and Raney once worked 35 hours straight through at Huntsville during Christmas holidays.[48] It was clear that the future of numerical modeling at the Station depended on the development of a more powerful computer capability.

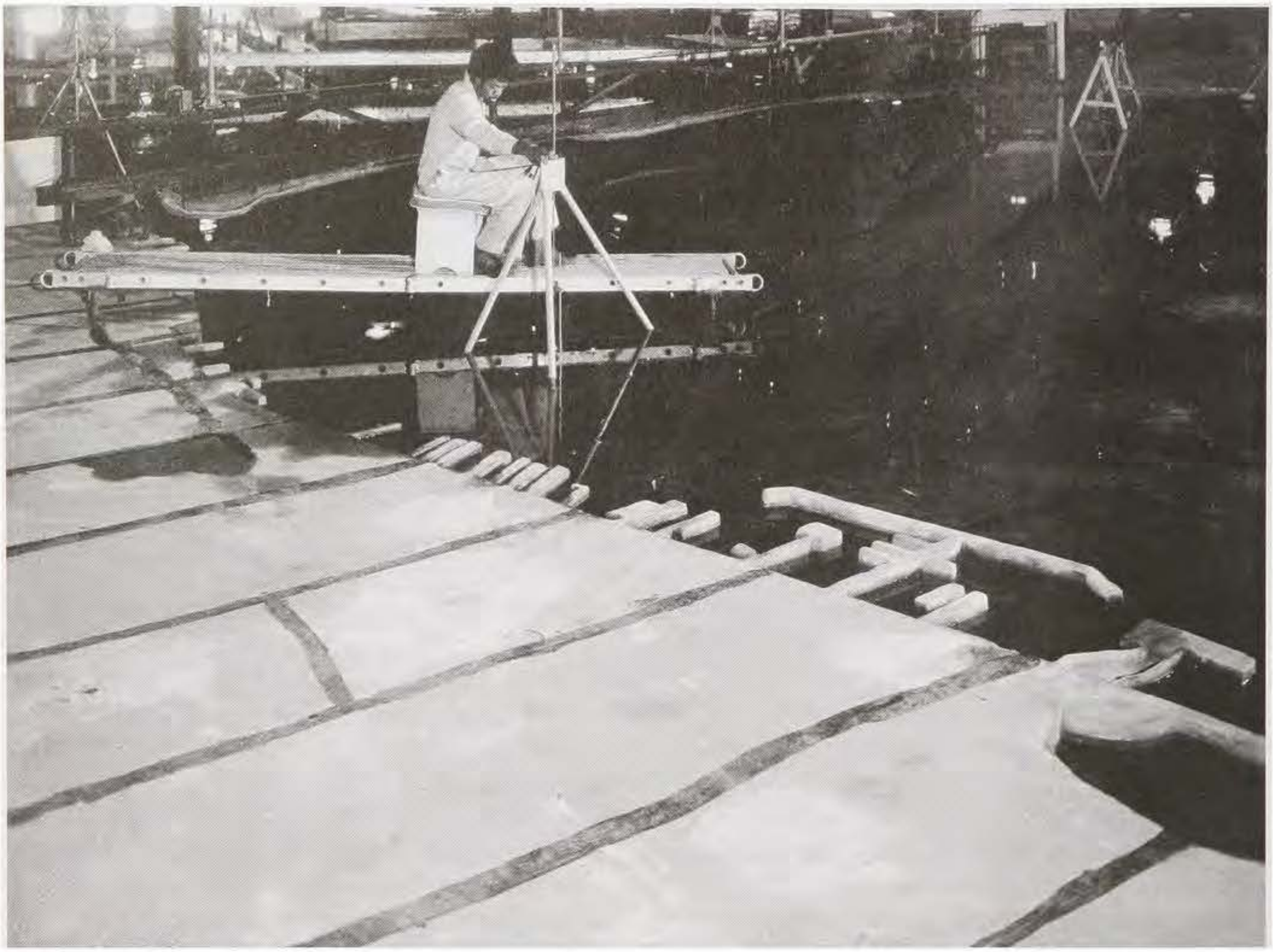
Conditions improved slowly. By 1978 the Hydraulics Laboratory had one in-house terminal that could communicate with large computer systems at Kirtland Air Force Base, New Mexico, and the Civil Service Commission at Macon, Georgia. The Automatic Data Processing Center had also acquired a Texas Instruments Advanced Scientific Computer (ACS) system valued at $8 million. Further WES purchases by the early 1980s included more advanced Honeywell DPS-1 and IBM 4331 models. Even these were not capable of handling the enormous computational load required for complex numerical modeling.[49] WES engineers continued to link electronically with outside computational sources, especially commercial entities such as the Boeing Corporation. This was inconvenient as well as very costly. According to a Boeing Cybernet salesman, McAnally's numerical modeling group within the Estuaries Division was the biggest user of commercial computer capacity in the entire Corps of Engineers.[50] Not until the late 1980s — with the acquisition of state-of-the-art supercomputers — was WES' in-house computer capability fully able to handle the demands of its research laboratories.

Turning Point: Columbia River Estuary

If the Los Angeles/Long Beach Harbor investigations represented a transitional phase in the acceptance of numerical estuary modeling, studies of the Columbia River Estuary in the late 1970s marked a clear turning point. In 1976 increased shoaling in the Columbia River Estuary led the Corps' Portland District to request a WES study. Although the University of California at Berkeley had built a physical model of the Columbia estuary as early as 1933, and WES had performed a major physical model study in the 1960s,[51] the treacherous prototype continued to plague engineers. Accordingly, in 1976 the Portland District requested that the Hydraulics Laboratory determine if newly-developed numerical modeling techniques could be applied to shoaling. A pilot study indicated that a hybrid modeling effort offered the potential to provide better results than had been available with physical models or with previously developed computer programs.[52]

The physical model of the Columbia estuary constructed at WES in 1961 was a cornerstone of the project. Inclusion of the physical model, it was felt, would provide an anchor of relatively well-known prototype data and behavior to a project with many innovative, but untested, elements. By the time of the pilot hybrid study, the physical model had been inactive for several years. Because it had been molded to hydrographic conditions of 1959, a number of alterations were necessary to reflect the substantial changes that had taken place in the interim. Fortunately, designers had molded the model's navigation channel with removable blocks so desired changes could be made with a minimum of difficulty. By 1977 the 44,000-square-foot structure had been revamped and reverified.

Numerical modeling of the estuary involved the integration of output from three separate computer models with data derived from the physical model. Each numerical model was designed to simulate different hydraulic phenomena. RMA-2 was a two-dimensional code to model hydrodynamics developed by Ian P. King, W.R. Norton, and Gerald T. Orlob of Water Resources Engineers for the Walla Walla District. King and Norton subsequently moved to Resource Management Associates (RMA) and made further enhancements. WES personnel then made major improvements culminating in RMA-2V. A second code, RFAC, modeled wave conditions. Numerical modeling of sediment transport, however, presented the greatest challenge. A review of available options indicated that SEDIMENT 2H, a model developed at the University of California at



Columbia River Estuary model

Davis by Ray B. Krone, Ranjan Ariathurai, and R.C. MacArthur, was most suitable. Because their work had been financed by the Corps' Dredged Material Research Program, WES had ready access and numerous professional connections.[53] Thomas, McAnally, and Ariathurai, first funded by the Portland District, then by OCE, led WES efforts that produced an upgraded descendant of SEDIMENT 2H entitled STUDH.[54]

Portland District and North Pacific Division engineers were at first surprised and seriously questioned the accuracy of Columbia estuary data produced by STUDH and the other numerical models. However, WES engineers insisted that their projections correctly indicated that channel enlargement would greatly increase shoaling rates. Prototype experience following construction of the enlarged channel demonstrated that STUDH had produced more accurate results than even its creators anticipated. The two-dimensional model predicted sediment transport, deposition, and erosion better than was possible in a physical model, even when coordinated with one-dimensional computer models. This led WES project directors to describe their Columbia estuary hybrid as "the most advanced production-level sedimentation modeling method in the world." Their boast, however, was tempered with the warning that three-dimensional models would be necessary to push numerical modeling to higher levels of accuracy.[55]

The success of numerical sediment modeling in the Columbia River project marked an acceptance for numerical estuary work at WES and by the Station's clients. It led directly to increased dependence on numerical modeling and a concomitant precipitous decline in the use of physical models. As McAnally had predicted, hybrid modeling appeared to be the transitional stage between physical and numerical estuary

modeling. By the early 1980s the Hydraulics Laboratory found it almost impossible to "sell" physical models to prospective sponsors. In the 1980s and 1990s WES engineers were able to create highly complex two- and three-dimensional programs that made numerical modeling of such intricate prototypes as Chesapeake Bay and the Atchafalaya estuary possible. Physical modeling of estuaries moved to the brink of extinction. Only one major physical estuary model in the United States remained in operation in the mid-1990s — the San Francisco Bay model functions primarily as a tourist attraction.[56]

The Corps, Dredging, and the Environment

In the 1970s, as the computer revolution whirred and hummed, the United States responded to generations of despoliation of the national environment by exhibiting a new respect for nature. Passage by Congress of the monumental National Environmental Policy Act (NEPA) at the end of 1969 and subsequent creation of the U.S. Environmental Protection Agency (EPA) soon affected nearly every aspect of American engineering practice. The Corps of Engineers' hydraulic and geotechnical projects were far from exceptions.

In fulfilling its mission in the development and maintenance of navigable waters, the Corps for decades had been responsible for the dredging of large volumes of sediment. Such sediments were called spoil until the 1970s when the less graphic term dredged material became the norm. By the early 1970s the quantity of material dredged by the Corps neared 400 million cubic yards per year, enough to build a wall six feet tall and three feet thick around the earth nine times, with costs exceeding $150 million. Typically, dredge operators simply deposited dredged material at the closest convenient site with little, if any, concern for possible environmental damage. Open water disposal was by far the most common method, with about two-thirds of all material dredged during maintenance operations disposed of in this fashion. Other dumping sites included adjacent shorelines and diked areas.[57]

Corps dredging posed numerous environmental questions

Due to rapid industrialization and population growth, material dredged from numerous harbors and channels was polluted with biological or chemical wastes, or both. Even in the absence of pollution, dredging had profound effects on ecological systems. As early as 1966 the Corps became concerned that polluted dredged material might have adverse effects on water quality and aquatic organisms and began investigating the feasibility of alternative dredged material disposal methods at selected harbors in the Great Lakes. However, early Corps studies assessing the environmental impact of dredging and disposal practices determined that very little objective data were available. It was obvious to Corps planners that a comprehensive program of research would be required to provide definitive information on the environmental impact of dredging and disposal of dredged material, both in open water and on land.[58]

The National Environmental Policy Act reflected national concerns about dredging by requiring detailed environmental impact statements for all proposed new navigation projects and all existing projects requiring maintenance dredging. This proved impossible because of the serious information deficiencies expressed in earlier Corps reports. In response, according to Simmons, over drinks at the Purple Tree Lounge in Savannah, GA, he and OCE Operations Division Chief Jacob Douma devised a plan for a dredged material research study. Douma had at one time in the 1930s worked at WES as yet another college-educated "laborer" on the Mississippi Flood Control Model. The two scratched out a proposal on a napkin that Simmons next saw as "a Congressional resolution directing the Corps to conduct this study....Evidently we had exactly the right brand."[59] Indeed, Congress in its 1970 River and Harbor Act directed the Chief of Engineers to conduct a "comprehensive program of research, study, and experimentation relating to dredged spoil."[60] OCE then assigned WES the two tasks of reviewing all existing literature and available data on dredged material and of developing guidelines for a comprehensive research program.[61]

In response to the OCE mandate, in 1971 WES established an interdisciplinary study team under Simmons' nominal direction. Original members included Project Leader Boyd and Captain R.D. Brown of the Mathematical Hydraulics Branch (formerly Mathematical Hydraulics Group); geologist Roger T. Saucier and soils specialist R.L. Montgomery of the Soils and Pavements Laboratory; and J.W. Keely, Lieutenant D.B. Mathis, and C.J. Guice of the newly-created Office of Special Assistant for Environmental Coordination. Harrison, who had left the Mathematical Hydraulics Group to become WES Special Assistant for Environmental Coordination, provided consultative assistance. (Harrison had remained at WES after completing active military service in 1969.) In April 1972 the group completed its report, published by WES as *Disposal of Dredge Spoil: Problem Identification and Assessment and Research Program Development.*[62]

Dredged Material Research Program

In February 1973 the Office of Management and Budget (OMB) approved the broad research program delineated in the WES report, with WES to assume responsibility for actual implementation. Anticipating a five-year project with a budget of $30 million, Station administrators the next month initiated a full-scale Dredged Material Research Program (DMRP) administered by an Office of Dredged Material Research (ODMR). Harrison headed the interdisciplinary group, which was to work in close coordination with the WES Office for Environmental Studies (successor to Harrison's post of Special Assistant for Environmental Coordination.) Although removed administratively from the auspices of the Hydraulics Laboratory, ODMR maintained a close relationship with the lab through Boyd, who served as liaison officer and planning consultant.[63]

Over the next 16 months the Office of Dredged Material Research began administration of four major long-term DMRP projects — Aquatic Disposal, Habitat Development, Disposal

Operations, and Productive Uses — each headed by a full-time high-level Project Manager with support staff. During the course of that period the ODMR grew to further include over a dozen outside consultants, an administrative support staff, a District Office Coordinator, and an Interagency Coordinator.[64]

Environmental Effects Laboratory

Environment-related activities burgeoned simultaneously in other WES laboratories. In 1972, for example, the Mobility and Environmental Laboratory began an Aquatic Plant Control Research Program for OCE that involved the use of herbicides, lasers, insects, pathogens, and plant-eating fish in the struggle to manage troublesome aquatic flora.[65] Reacting to changing national concerns and Corps priorities, in July 1974 WES combined the Office of Dredged Material Research and the Office for Environmental Studies to form a new Environmental Effects Laboratory with Harrison as Chief. (In 1978 WES administrators changed the name to the more succinct Environmental Laboratory and gave it control of all environmentally-focused civil investigations for the Station.) The new entity took its place as an administrative equal to the Hydraulics and Geotechnical Laboratories. As with the establishment of Nuclear Weapons Effects Laboratory, activities that originated primarily in the Hydraulics Laboratory had led to the creation of a new research organization headed by a former Hydraulics Laboratory engineer.

Wave Dynamics Division: Great Lakes Study

Problems with dredged material, in addition to prompting creation of the Dredged Material Research Program, involved the Hydraulics Laboratory's Wave Dynamics Division in a unique project: numerical modeling of wave actions on the Great Lakes. Developing a dredged material disposal program for the Great Lakes region fell to the Corps' North Central Division. By 1974 the division had adopted a plan calling for 41 diked disposal sites constructed in the lakes, along the shoreline, or in the lee of breakwaters. Corps planners feared the program would be extraordinarily expensive, with construction to cost approximately $500 million and preliminary field studies alone about $500,000. The field studies, it was felt, would be necessary to determine design wave conditions throughout the Great Lakes region.[66]

Collection of data by field studies could provide accurate data, but had inherent disadvantages. A lengthy period of data collection would be necessary — estimated at several years — requiring a large and expensive network of towers and buoys. North Central Division personnel consequently wondered whether a numerical model could be developed to provide information about wave action at any point on the Great Lakes without the necessity of field studies. Such a model would rely on hindcasting: the technique of using a numerical model and chronological data to construct a past wave history, thus creating a statistical base to predict future wave activity.[67]

The North Central Division's questions met with discouraging responses from the Coastal Engineering Research Center (CERC), which considered design of a wave-forecasting numerical model to be beyond the state of the art. At WES, however, the Hydraulics Division's Wave Dynamics Branch (formerly Water Waves Branch) was optimistic. By the late 1960s the branch had shrunk to a relatively small group involved primarily in breakwater and small harbor design. Then Whalin, who replaced Hudson as Wave Dynamics Branch Chief in 1971, breathed new life into its programs. Having earned a Ph.D. in physical oceanography from Texas A&M University, Whalin had published a large number of technical papers and was well familiar with the numerical modeling techniques gaining acceptance in the field.[68]

In the spring of 1974, with the possibility of a major Great Lakes study in mind, Whalin hired two recent Ph.D. graduates from the University of Virginia — Donald T. Resio and C. Linwood Vincent. Both were advocates of numerical modeling and Resio's doctoral dissertation had dealt with hindcasting wind and wave conditions. All were convinced that a numerical model of wave action on the Great Lakes could be developed quicker and cheaper than field studies. Finally, due to Whalin's efforts, in July 1974 the North Central Division committed funds to WES for a Great Lakes Wave Information Study, the focus of which was development of a numerical wave-prediction model.[69]

Donald T. Resio

C. Linwood Vincent

Resio and Vincent worked constantly on the project for the next two years. In Resio's opinion, since wave action on the Great Lakes was almost entirely the product of winds, the success of a numerical model depended primarily on the model's ability to accurately predict wind conditions over the lakes. Knowing wind conditions over the lakes would enable engineers to calculate attendant wave conditions. Although a huge database existed for wind and wave conditions on the *shores* of lakes and adjacent areas, little continuous data were available for conditions *over* the lakes. Resio and Vincent then faced the task of assimilating decades of empirical data to establish theoretical relationships between winds over land and winds over lakes and between winds over lakes and the waves they generated. Because adequate computer facilities were available only at Los Alamos, and there only on weekends, Resio and Vincent often worked full-time weekdays at the Station, then commuted to New Mexico for the weekends. There they sometimes toiled through entire two-day periods with little or no sleep.[70]

In a joint program of verification, WES and CERC determined that the Resio/Vincent numerical model produced results even more reliable than had been hoped. A succeeding series of five *Technical Reports* authored by Resio and Vincent and published by WES between 1976 and 1978 defined the state of the art in wind/wave numerical analysis and established the Wave Dynamics Division (formerly Wave Dynamics Branch) as a world leader in the field.[71]

Ocean Wave Information Study

WES success in the Great Lakes study led researchers to conclude that hindcasting techniques could be applied to other bodies of water — even to the Atlantic and Pacific Oceans. Resio and Vincent, in fact, believed that they could extend their work to all the nation's seashores. As a first step, the South Atlantic Division was prepared to fund a WES investigation of hindcasting in the Atlantic Ocean. This embroiled WES in a controversy with CERC, which claimed that such a study should be under its purview. Intervention by OCE resulted in the study's assignment to the WES Wave Dynamics Division. The South Atlantic Division was to provide the first year's funding, with OCE taking over funding for the second.[72]

In the early stages of the Ocean Wave Information Study, Resio and Vincent attempted to apply their Great Lakes model to the entire North Atlantic Ocean. However, the model predicted more wave action than field data confirmed. After three months of reanalysis, the WES engineers discovered and corrected an error in their program, after which the study proved successful.[73] In the meantime, other notable WES projects contributed to the rise of the Wave Dynamics Division as an international leader in coastal engineering and numerical modeling. Houston, for instance, led Hydraulics Laboratory efforts to develop a numerical sediment transport model used at Oregon Inlet in the North Carolina Barrier Islands and also

devised a numerical model to determine the inundation limits of tsunamis in the Hawaiian Islands and for the continental U.S. Pacific coast.[74]

WES versus CERC

Development of research capabilities by the WES Wave Dynamics Division posed a serious threat to the viability of the Coastal Engineering Research Center. The Center's forerunner, the Beach Erosion Board (BEB), had helped guide Corps efforts in coastal engineering since 1930, largely under the leadership of Morrough P. O'Brien. In 1963 OCE established CERC on a reservation at Dalecarlia Reservation in Washington, D.C. Answering directly to OCE, the Center was intended to be the Corps' primary facility for coastal research. Unlike WES, CERC received a direct appropriation from the Corps and was not to engage in reimbursable site-specific projects.

From its inception, CERC had strong WES ties. Its first Technical Director, Joseph M. Caldwell had begun his engineering career at WES in 1933. A native of Yazoo City, Mississippi, and graduate of Mississippi State College, Caldwell served briefly as WES Hydraulics Division Chief in 1941 and 1942 when Eugene Fortson was called to active duty. In 1942 Caldwell also reported for active duty and served on the staff of the Chief of Engineers through World War II. When he was unable to return to WES as Laboratory Chief, in 1946 he joined the Beach Erosion Board's Research Division, heading it from 1951 to 1963. He then became Technical Director of CERC. As CERC's leader from 1963 to 1971, Caldwell maintained close relations with WES while enduring personnel problems, reorganization, and a difficult move from the Dalecarlia Reservation to Fort Belvoir. In 1971 he rose to the position of Chief of Engineering Division, Civil Works, OCE. Thorndike Saville, Jr., son of a former BEB member, succeeded Caldwell at CERC.[75]

Efforts at CERC and WES often overlapped, sometimes with controversial results. In the mid-1960s, for example, OCE sanctioned a General Investigation of Tidal Inlets (GITI) basic research program. Work was to take place at four facilities — three large test basins at WES and one at CERC. WES began construction of Facility A, which was to simulate inlets of various characteristics under different tidal conditions; Facility B that would consist of an "ocean" in which tides of various periods and amplitudes could be generated, a "lagoon," and a connecting section; and Facility C, the largest at 350 feet long by 150 feet wide, was to have a movable-bed "ocean" equipped with appurtenances for generating tides, waves, littoral currents, and other forces, plus a fixed-bed "lagoon" and a connecting movable-bed beach and inlet section.[76]

Understanding that the work was to be basic research rather than site-specific studies, CERC in Fiscal Year 1965 and Fiscal Year 1966 allocated $165,000 to WES for construction of its three test basins. However, WES designers altered the models so that they could be used for site-specific experiments. The Coastal Engineering Research Board — CERC's advisory body — then demanded that CERC be given control of the three facilities at WES. The dispute reached OCE, which made a decision intended to appease both CERC and WES. The Hydraulics Division's Wave Dynamics Branch, which was to conduct tests in the three WES basins, would continue to control their use, but would be restricted to basic research rather than applied research for project studies. Denied the opportunity to perform project research, the WES Branch dwindled to about six people engaged mainly in breakwater design tests.[77]

State-of-the-art electrohydraulic wave generator

Rise of the Wave Dynamics Division

Overcoming temporary setbacks, the Wave Dynamics Branch (Division after 1972) challenged, then surpassed CERC as the Corps' primary institution for coastal engineering. As a first step in revitalizing the WES unit's workload, in 1969 the Coastal Engineering Research Board compressed a 10-year tidal inlet model studies program to be performed by the Branch into five.[78] Second, the Wave Dynamics Division's role in the construction and operation of the Los Angeles/ Long Beach Harbor model from 1972 to 1974 placed it at the forefront of computer-controlled physical harbor modeling and complementary numerical modeling. Of special note, design and procurement of the model's electrohydraulic wave generator marked a quantum improvement in the Station's ability to simulate complicated wave regimes. The apparatus consisted of 14 separate 15-foot-long units capable of generating wave lengths up to 210 feet with variable heights, periods, and with curved fronts.[79] This enabled the Division to study model waves more like those in complex prototypes. Also, the WES organization successfully conducted the Great Lakes wind hindcast study when CERC declined to offer, and preempted the Center's attempt to perform ocean wind hindcasts.

Robert W. Whalin

Whalin's aggressive leadership was another contributing factor to the rise of the Wave Dynamics Division. Intent on molding it into a world-class organization, he faced two major problems: recruiting engineers familiar with numerical modeling techniques, and acquiring new, expensive experimental equipment.[80] Support for the first came with the Army's assignment of Houston to WES and the hiring of Resio, Vincent, and other young engineers experienced in computer usage. A California native with degrees in physics from the

James R. Houston

University of California at Berkeley and the University of Chicago, Houston earned a Ph.D. from the University of Florida in 1978 as a participant in the Station's graduate education program.[81]

In its struggle to acquire needed experimental equipment, WES had an inherent advantage over CERC: the Station could borrow from the Corps' revolving fund, then repay the debt by performing reimbursable work for clients. Whalin was convinced that to move to the forefront, the Wave Dynamics Division must have a multidirectional, spectral wave generator. Such a device would rely on a variable signal sent from a computer to wave-generating boards to create waves differing in height and period and traveling in any direction. None yet existed, although a $25 million facility was being built in Norway. In a major commitment, WES directors in 1978 succeeded in getting OCE approval of a plan submitted by Whalin to construct a new test basin with a multidirectional spectral wave generator designed by the Wave Dynamics Division. When completed in 1979, the facility gave WES capabilities in wave research far beyond those of CERC.[82]

Transfer of CERC to WES

By the 1980s the Corps faced the dilemma of maintaining two research organizations with overlapping functions during times of budgetary reform. In a decision fraught with political infighting and intrigue, in February 1982 the Chief of Engineers endorsed a recommendation from the Corps' Directorate of Research and Development to relocate CERC to Vicksburg. Even before the decision was made public, Whalin reported to Fort Belvoir in March 1982 to become CERC Technical Director. The move took place in 1983 only after vigorous protests from many CERC employees and intervention by most of the Virginia congressional delegation. Of the 83 CERC personnel offered transfers to WES, only 24 accepted; of those, two had been hired from WES in 1982 and one had been hired by CERC for transfer to WES.[83]

The move to Vicksburg, rather than marking the demise of the Coastal Engineering Research Center, led to its emergence as the world's premier institution in coastal research. In consolidating and bolstering the Center's mission, WES administrators removed the Wave Dynamics Division from the Hydraulics Laboratory and united it with the existing CERC divisions. Now with access to state-of-the-art experimental equipment and with a staff well-versed in numerical modeling, CERC took its place as an equal to the other WES research units. Yet again, expanded activities of the Hydraulics Laboratory had led to the establishment of an entity new to the Station headed by a former Laboratory engineer. (Whalin headed CERC until 1985 when he became WES Technical Director. James Houston, also formerly of the Wave Dynamics Division, succeeded Whalin as CERC Chief.)

Notes

1. J.J. Stoker, "Numerical Solution of Flood Prediction and River Regulation Problems," 2 reports (New York: New York University Institute of Mathematical Sciences, 1953-1954); prepared for U.S. Army Engineer Division, Ohio River, under Contract DA-33-17-eng-223.

2. Letter, Major General B.L. Robinson, Deputy Chief of Engineers for Construction, to Brigadier General John H. Hardin, Chairman, Mississippi Basin Model Board, 26 April 1954. Arthur T. Correspondence File, Institute Archives, Massachusetts Institute of Technology. Copy in Research Collection of the Office of History, HQ, U.S. Army Corps of Engineers, Alexandria, Virginia.

3. Ibid.

4. Ibid. Also letter, J.B. Tiffany, WES Technical Director, to Arthur T. Ippen, 3 August 1954. Arthur T. Ippen Correspondence File, Institute Archives, Massachusetts Institute of Technology. Copy in Research Collections of the Office of History, HQ, U.S. Army Corps of Engineers.

5. Letter, Arthur T. Ippen to Colonel C.H. Dunn, WES Director, 6 August 1954. Arthur T. Ippen Correspondence File, Institute Archives, Massachusetts Institute of Technology. Copy in Research Collections of the Office of History, HQ, U.S. Army Corps of Engineers, Alexandria, Virginia.

6. Tiffany, *History of WES*, X-5-6.

7. H.B. Simmons, "Protection of Narragansett Bay from Hurricane Surges. Summary Report, Hydraulic Model Investigation," WES *Technical Report No. 2-662* (Vicksburg: WES, 1964).

8. For U.S. Navy interest in the project, see J.G. Housley, "Effects of Hurricane Barrier on Navigation Conditions in East Passage, Narragansett Bay, Rhode Island, Hydraulic Model Investigation," WES *Technical Report No. 2-754* (Vicksburg: WES, 1967).

9. Simmons, "Protection of Narragansett Bay." Also see N.J. Brogdon, "Galveston Bay Hurricane Surge Study, Report 1: Effects of Proposed Barriers on Hurricane Surge Heights. Hydraulic Model Investigation," WES *Technical Report H-69-12* (Vicksburg: WES, 1969).

10. Brogdon, "Galveston Bay Hurricane Surge Study."

11. Robert O. Reid and Bernie R. Bodine, "Numerical Model for Storm Surges in Galveston Bay," *American Society of Civil Engineers: Journal of the Harbors and Waterways Division* 94 WW1 (1968): 33-56.

12. Letter Colonel C.H. Dunn to Arthur T. Ippen, 27 January 1954, Arthur T. Ippen Correspondence File, Institutional Archives, Massachusetts Institute of Technology. Copy in Research Collections of the Office of History, HQ, U.S. Army Corps of Engineers, Alexandria, Virginia.

13. Marden B. Boyd, interview by author, Vicksburg, 29 August 1995.

14. *Report of Fourth Conference, Hydraulics Consultants Board, 18-19 January 1968* (Vicksburg: WES, 1968).

15. Marden B. Boyd interview.

16. *Report of Fourth Conference, Hydraulics Consultants Board.*

17. Henry B. Simmons interview.

18. *Report of Fifth Conference, Hydraulics Consultants Board, 22-24 January 1969.*

19. *Report of Sixth Conference, Hydraulics Board of Consultants, 21-23 January 1970.*

20. *Report of Seventh Conference, Hydraulics Consultants Board, 27-29 January 1971* (Vicksburg: WES, 1971).

21. See M.A. Granat, L.F. Gulbrandsen, and V.R. Pankow, "Reverification of the Chesapeake Bay Model: Chesapeake By Hydraulic Model Investigation," WES *Technical Report HL-85-3* (Vicksburg: WES, 1985).

22. Richard A. Sager, interview by author, Vicksburg, 31 May 1996. After completion, the model was once snowed in, stranding employees for several days.

23. Ibid.

24. Henry B. Simmons interview by Michael Robinson.

25. Minutes, First Meeting, Chesapeake Bay Study Advisory Group. Cited in Pendergrass, 239.

26. Pendergrass, 241. Pendergrass cites *Minutes of the 66th Meeting, Committee on Tidal Hydraulics, 15-16 July 1969* for Lockett's comments. Masch's response to Lockett is included with the committee minutes.

27. Pendergrass, 242. Pendergrass cites a letter from Joseph B. Tiffany to the Chief of Engineers, 15 April 1969, in Records of the Chief of Engineers, Washington National Records Center, Suitland, Maryland, Accession No. 77-73-039, Box 1, File 1507-01.

28. Among many descriptions of the Chesapeake Bay model are those of Samuel B. Heltzel, "Chesapeake Bay Hydraulic Model," *The Military Engineer* 70 (1978), 230-33; and Samuel B. Heltzel and Mitchell A. Granat, "The Chesapeake Bay Hydraulic Model: Construction, Operation, and Verification," in Malcolm M. Spaulding, ed., *Estuarine and Coastal Modeling: Proceedings of the Conference Sponsored by the Coastal Zone Management Committee of the Waterway, Port, Coastal and Ocean Division of the American Society of Civil Engineers, November 15-17, 1989* (New York: American Society of Civil Engineers, 1990), 239-47.

29. See Norman W. Scheffner, Leroy G. Crosby, David F. Bastian, A. Michael Chambers, and Mitchell A. Granat, "Verification of the Chesapeake Bay Model," WES *Technical Report HL-81-14* (Vicksburg: WES, 1981).

30. Richard A. Sager, interview.

31. Scheffner et al., "Verification"; also Heltzel, "Chesapeake Bay Hydraulic Model."

32. Roger H. Multer, "Planning of Automated Data Acquisition and Process Control Systems (ADACS)," WES *Miscellaneous Paper HL-80-1* (Vicksburg: WES, 1980).

33. Ibid.

34. "Hydraulic Model Testing Begins," *Chesapeake Bay Study News Circular* (U.S. Army Corps of Engineers Baltimore District) 1 (1978).

35. See, for example, M.A. Granat and L.F. Gulbrandsen, "Baltimore Harbor and Channels Deepening Study; Chesapeake Bay Hydraulic Model Investigation," WES *Technical Report HL-82-5* (Vicksburg: WES, 1982).

36. M.A. Granat, L.F. Gulbrandsen, and V.R. Pankow, "Reverification of the Chesapeake Bay Model; Chesapeake Bay Hydraulic Model Investigation," WES *Technical Report HL-85-3* (Vicksburg: WES, 1985).

37. William H. McAnally, interview by author, Vicksburg, 22 May 1996.

38. Ibid.

39. Ibid. McAnally later earned a Ph.D. at the University of Florida.

40. An excellent discussion of hybrid modeling is included in William H. McAnally, Jr., Noble J. Brogdon, Jr., Joseph V. Letter, Jr., J. Phillip Stewart, and William A. Thomas, "Columbia River Estuary Hybrid Model Studies. Report 1: Verification of Hybrid Modeling of the Columbia River Mouth," WES *Technical Report HL-83-16* (Vicksburg: WES, 1983).

41. McAnally interview.

42. W.H. McAnally "Problems and Solution Methods, Kaneohe Bay, Hawaii," in "Engineering and Scientific Research at WES," WES *Miscellaneous Paper 0-75-5* (Vicksburg: WES, 1975). The full study is contained in W.H. McAnally, J.D. Lunz, D.C. Raney, R.Y Hudson, and J.V. Letter, "Problem Definition and Modeling Techniques for the Study of Kaneohe Bay, Oahu, Hawaii," WES *Research Report H-74-2* (Vicksburg: WES, 1974).

43. See Leroy G. Crosby and Donald L. Durham, "Los Angeles and Long Beach Harbors Model Study, Report 1, Prototype Data Acquisition and Observations," WES *Technical Report H-75-4* (Vicksburg: WES, 1975).

44. Ibid. Also see Leroy G. Crosby and Donald L. Durham, "Los Angeles and Long Beach Harbors Model Study, Report 2, Observations of Ship Mooring and Movement," WES *Technical Report H-75-4* (Vicksburg: WES, 1975); and William H. McAnally, "Los Angeles and Long Beach Harbors Model Study, Report 5, Tidal Verification and Base Circulation Tests," WES *Technical Report H-75-4* (Vicksburg: WES, 1975).

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47. James R. Houston, "Long Beach Harbor Numerical Analysis of Harbor Oscillations," WES *Miscellaneous Paper H-76-20* (Vicksburg: WES, 1976); James R. Houston, "Los Angeles Harbor

Numerical Analysis of Harbor Oscillations," WES *Miscellaneous Paper H-77-2* (Vicksburg: WES, 1977); James R. Houston, "Los Angeles Harbor and Long Beach Harbor: Finite Element Numerical Model of Harbor Resonance," in *Ports '77: 4th Annual Symposium of the Waterway, Port, Coastal and Ocean Division of ASCE* (New York: American Society of Civil Engineers, 1977), 1: 119-135; William H. McAnally and Donald C. Raney, "Los Angeles Harbor and Long Beach Harbor: Physical and Numerical Tidal Models: A Comparison," in *Ports '77: 4th Annual Symposium of the Waterway, Port, Coastal and Ocean Division of ASCE* (New York: American Society of Civil Engineers, 1977), 1: 101-118; and McAnally interview.

48. William H. McAnally interview; also Carl J. Huval, interview by author, Vicksburg, 11 June 1996.

49. The evolution of computer capacity is summarized in the WES *Annual Summary* series published for each fiscal year beginning in 1978.

50. McAnally interview.

51. WES modeling efforts are detailed in F.A. Herrmann and H.B. Simmons, "Model Studies of Navigation Improvements, Columbia River Estuary," 3 reports, WES *Technical Report 2-735* (Vicksburg: WES, 1966-1974).

52. A full discussion of the WES role in Columbia Estuary hybrid modeling efforts is included in William H. McAnally, Jr., Noble J. Brogdon, Jr., Joseph V. Letter, Jr., J. Phillip Stewart, and William A. Thomas, "Columbia River Estuary Hybrid Model Studies," 4 reports, WES *Technical Report HL-83-16* (Vicksburg: WES, 1983); and William H. McAnally, Joseph V. Letter, Jr., J. Phillip Stewart, W. Anthony Thomas, and N. James Brogdon, "Columbia River Hybrid Modeling System," *American Society of Civil Engineers: Journal of Hydraulic Engineering* 110 (1984) No. 3: 300-310; and William H. McAnally, Joseph V. Letter, Jr., J. Phillip Stewart, W. Anthony Thomas, and N. James Brogdon, "Application of Columbia Hybrid Modeling System," *American Society of Civil Engineers: Journal of Hydraulic Engineering* 110 (1984) No. 5: 627-42.

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59. Henry B. Simmons interview.

60. River and Harbor Act of 1970, Section 123 (i); Public Law 91-611.

61. Boyd et al., "Disposal of Dredge Spoil."

62. Ibid.

63. *Dredged Material Research Program: First Annual Report* (Vicksburg: WES, 1974); *Dredged Material Research Program: Second Annual Report* (Vicksburg: WES, 1975); *Dredged Material Research Program: Third Annual Report* (Vicksburg: WES, 1976); and Marden B. Boyd interview.

64. Ibid.

65. Details of the Mobility and Environmental Laboratory's activities in the Aquatic Plant Control Research Program are contained in a lengthy series of WES *Miscellaneous Papers* and *Technical Reports* published under the heading *Aquatic Plant Control Research Program.*

66. An excellent discussion of the WES role in the Great Lakes study is included in Jamie W. Moore and Dorothy P. Moore, *History of the Coastal Engineering Research Center, 1963-1983. Volume I: WES Laboratory History Series* (Vicksburg: WES, 1991), 56-58. The Moore's history of the Coastal Engineering Research Center ends with its transfer to WES in 1983.

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81. Biographical information on James R. Houston provided by WES Public Affairs Office. Also, James R. Houston, interview by author, Vicksburg, 15 June 1999.

82. Moore, 65-66.

83. Moore, 63-72, provides a highly detailed account of the decision to relocate CERC to Vicksburg and the resulting tumult.

8 The Computer Revolution, 1963-1983, Part II: Waterways and Hydraulic Structures

Rivers and Hydraulic Structures: Physical Modeling Vindicated

Throughout the 1960s and 1970s, while computerization revolutionized estuary and wave dynamics modeling, WES research in river navigation and hydraulic structures design retained a more traditional focus. Both river engineering and structures design, in fact, continued to rely largely on physical models that were accurate, relatively cheap, and less labor-intensive than their estuarine or harbor counterparts. Experiments concerned with huge projects to overhaul existing navigation systems on the Mississippi and Ohio Rivers or to design and build new systems on undeveloped rivers such as the Arkansas and Red proved that many physical river modeling techniques developed in the 1930s were still valid into the 1980s. Design of structures, especially in the expanding WES lock program, further confirmed the value of conventional modeling. Only in the areas of floodwater routing, lock operation, and barge traffic routing did computerization play an vital role in river engineering and structures design prior to the 1980s.

Ohio River Overhaul

Twentieth-century commerce on the Ohio River relied on an extensive program of river engineering. In 1910 Congress authorized development of a 9-foot-deep slackwater channel for the nearly thousand-mile length of the Ohio from Pittsburgh to Cairo. This led to construction of a network of 46 locks and dams.[1] Designed primarily to transport barges of coal and steel down the Ohio, each dam generally had a single 110-by-600-foot lock with lifts of less than 8.5 feet. By the time it was completed in 1929, the system already carried 50 percent more traffic than had been considered for project justification, and upstream traffic approached the volume of downstream traffic. In 1950 even that volume had more than doubled. Longer tows required double lockage at the 600-foot locks and some of the mechanical equipment of the locks was in need of frequent overhaul. (Double lockage meant that tows had to be broken in half, passed through the locks separately, then reunited.) Future transportation on the Ohio clearly depended on a comprehensive program of modernization.[2]

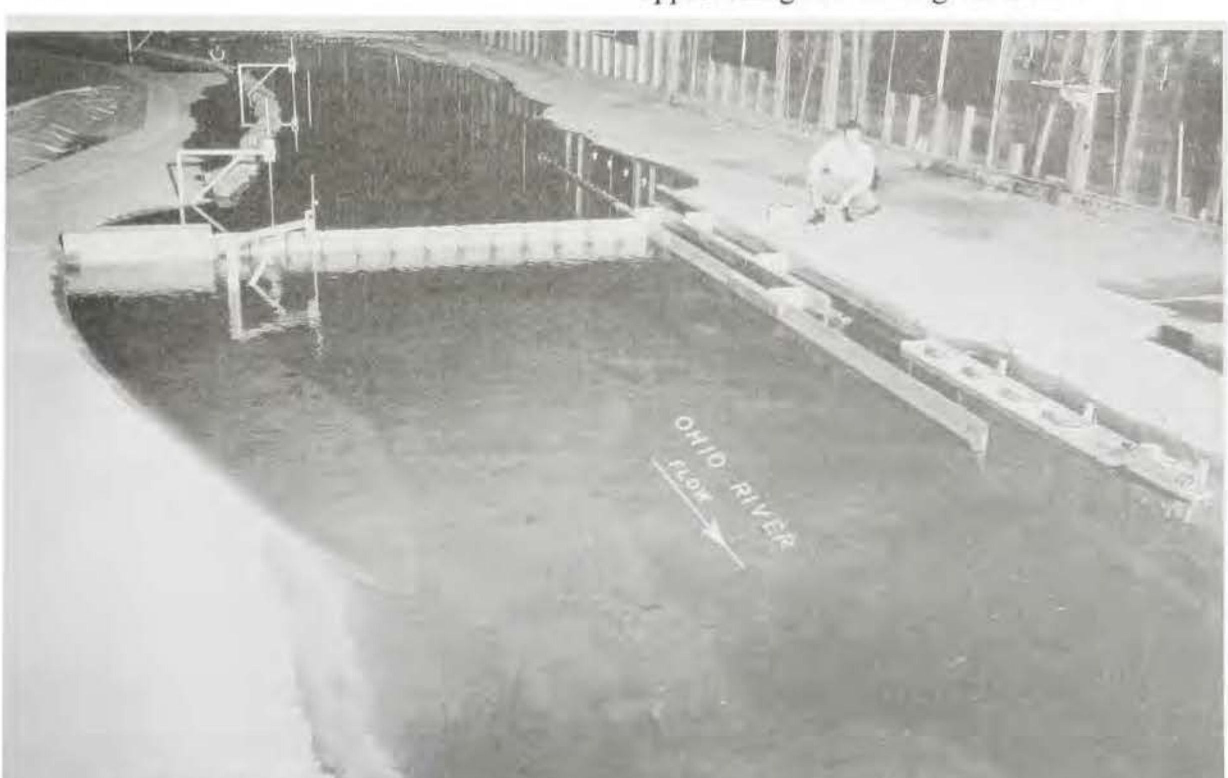
In the mid-1950s the Corps began a major overhaul of the Ohio River system. Plans called for construction of 19 new complexes with higher, non-navigable dams and dual locks. The taller dams were to provide longer slackwater pools,

eliminating the need for several of the older dams, while new 110-by-1,200-foot main locks and 110-by-600-foot auxiliary locks could handle the largest tows in use.[3]

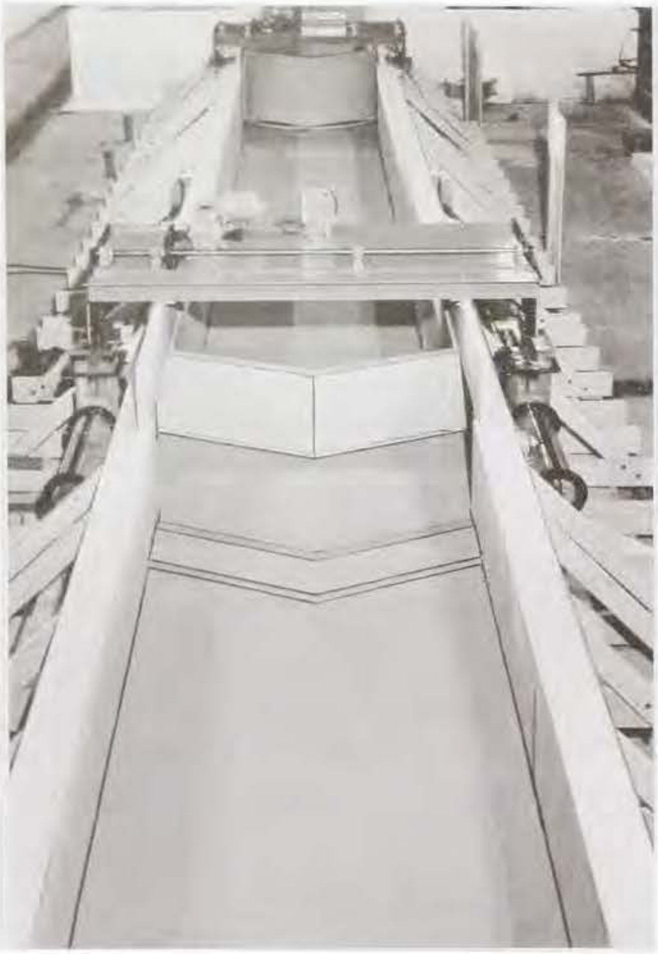
Ohio River Locks and Dam Studies

Insertion of new structures or removal of existing structures from a dynamic waterway such as the Ohio River would cause major changes in hydraulic conditions. Thus even before the Corps adopted a detailed plan for modernization of the Ohio River navigation system the Louisville District requested WES model studies to determine the best location and arrangement of locks and appurtenant structures and to provide optimal navigation conditions both during and after construction. From 1952 to 1956 Fenwick and Franco of the Waterways Branch conducted a lengthy series of experiments involving proposed Markland Locks and Dam and Greenup Locks and Dam. Markland Locks and Dam, the first new complex to be built, was to be located about equidistant between Cincinnati and Louisville and would replace five outdated locks and dams immediately upriver (Locks and Dams Nos. 35, 36, 37, 38, and 39). Greenup Locks and Dam was to be about 90 miles farther upriver. To involve and satisfy commercial interests, representatives of barge companies were allowed to observe model tests and make suggestions.[4]

The Markland and Greenup Locks and Dam studies marked a departure from earlier WES river modeling, which had dealt almost exclusively with flood control or river regulation. They also served as archetypes for future modeling of proposed navigation structures on the Ohio and other rivers. Throughout the 1960s and 1970s, WES model experiments supervised by Franco, Louis J. Shows, Cody D. McKellar, and Thomas J. Pokrefke led to site selection, design, and construction procedures for Uniontown, Cannelton, McAlpine, Smithland, Gallipolis, and other Ohio River locks and dam complexes. Like the earlier Markland and Greenup studies, all involved model reproduction of a relatively short river reach, typically less than 10 miles, the insertion of miniature locks and dam systems, and performance of tests to evaluate navigation conditions. Model operators used lilliputian electric-powered towboats and tows to determine the effects of currents on tows approaching and leaving the locks.[5]



Markland Locks and Dam model


McAlpine Lock model

Complementing the activities of the Waterways Branch (later Division) in the Ohio River project, the Structures Branch (later Division) under Murphy and John L. Grace played an integral role in the design of lock filling and emptying systems. Anticipating a great expansion in its lock building mission, the Corps had consolidated its lock design program at WES in late 1961. OCE particularly looked to the Station to develop standardized lock dimensions and hydraulic systems that could be generally applied. At a conference at WES in April 1962 representatives of OCE, the WES Hydraulics Division, the Ohio River Division, and its Louisville, Pittsburgh, and Huntington Districts agreed that WES should initiate a consolidated testing program of sidewall port filling systems that could be used throughout the Ohio River navigation project.[6]


John L. Grace

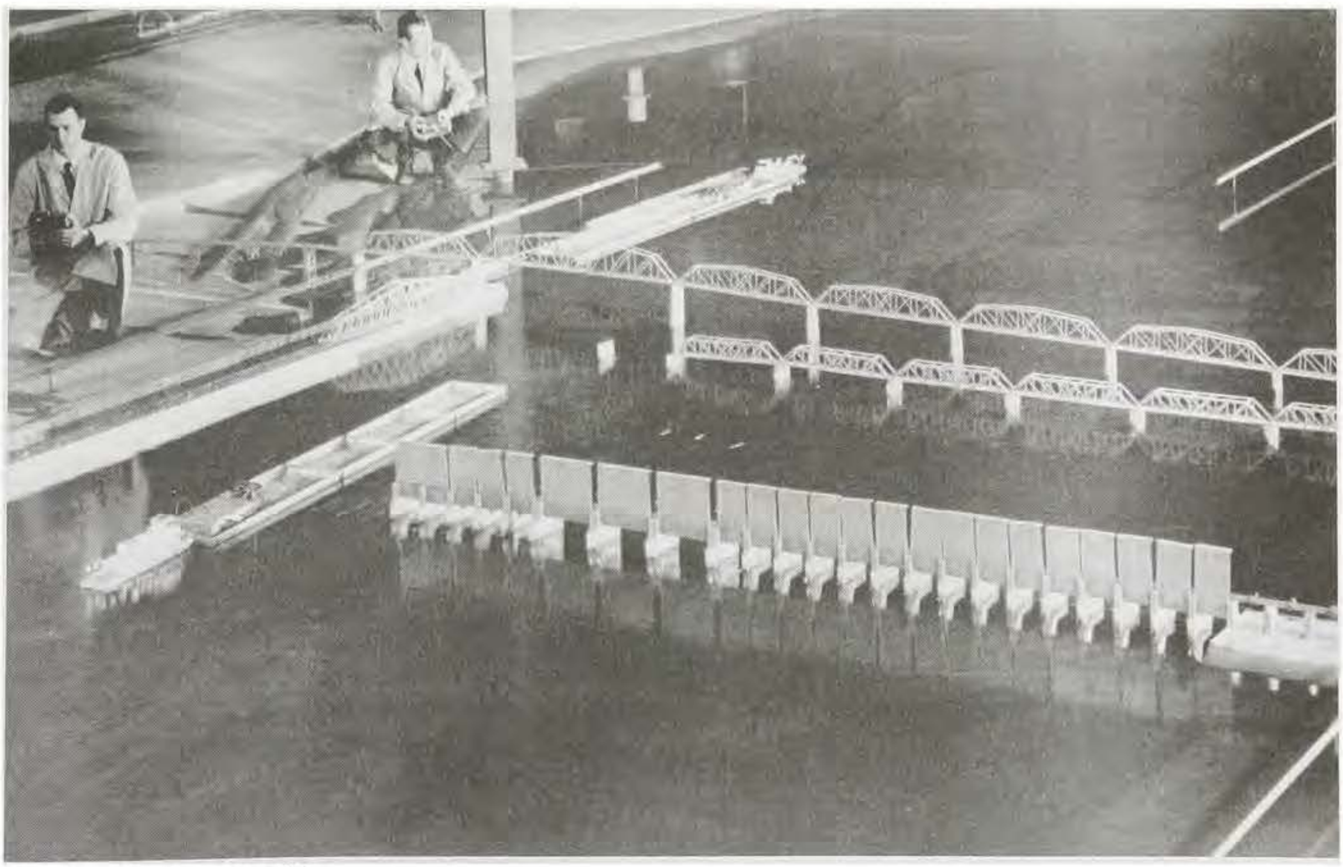
Jackson H. Ables and Boyd, then Locks Section Chief, spearheaded an effort to determine the efficiency of existing lock design criteria and to make improvements if necessary. Because Cannelton Lock was the next to be constructed, WES used it as a prototype for two hydraulic models. The first, used to study navigation conditions at the project, was a general model that included the upper and lower river approaches, the entire spillway, and the two navigation locks. A second model reproduced only the main lock and was used to evaluate its filling and emptying systems. By July 1964 the Station had tested over fifty sidewall port arrangements and made recommendations that were incorporated into Cannelton Lock and later Ohio River structures. The Cannelton design permitted the lock to be filled in about eight minutes and emptied in less than ten minutes, saving about ten minutes over previous lockage projections.[7]

Locks and Dam 26: Key to the Upper Mississippi River

On the existing Mississippi River navigation system, Locks and Dam No. 26 presented engineering challenges compounded by environmental, commercial, and political entanglements. Creation of a system of locks and dams on the Upper Mississippi dated from the River and Harbor Act of 1927. Congress thereby authorized a study of the Mississippi River from the mouth of the Missouri River north to Minneapolis with the purpose of establishing a 9-foot-deep navigation channel at low water. In 1930 a blue-ribbon panel recommended the construction of 24 locks and dams between Alton, IL, and Minneapolis in addition to improvements to the three small lock and dam complexes already in existence. (One recommended new lock and dam was deleted from the system before construction.) In a flurry of activity, the Corps essentially completed the project in 1940 at a cost of only $124 million.

As the next-to-lowermost complex of the Upper Mississippi River navigation project, receiving traffic from the Mississippi, Missouri, and Illinois Rivers, Locks and Dam No. 26 was the key to the entire system. Its gated dam and two locks, a 110-by-600-foot main lock and 110-by-360-foot auxiliary lock, were located approximately 20 miles above St. Louis. About 12 miles above St. Louis and eight miles below Locks and Dam No. 26 the Missouri River flowed into the Mississippi. The Illinois River flowed into the Mississippi about 15 miles above the locks and dam. Because the Illinois provided waterway access to Chicago and thence to Lake Michigan, Locks and Dam No. 26 was vital to access not only to and from Minneapolis and other Upper Mississippi River ports, but to traffic between the Lower Mississippi River and the Great Lakes. If the facility were inoperable for any reason, the delay could produce a bottleneck in the entire 17,000-mile Mississippi River system.[8]

Although planners apparently hoped for a 50-year project life, even by the 1950s, Locks and Dam No. 26 suffered from structural problems and inadequate lockage capacities. Its poor location caused further difficulties. The upstream approach channel was not properly aligned with the main lock because of a rock bluff jutting into the river about 1,500 feet above the lock. (The St. Louis District Engineer had selected lock location on the basis of a model study by the Corps' U.S. Engineer Sub-Office at Iowa City.[9]) An ongoing maintenance and repair program prevented structural deficiencies from threatening the integrity of the edifice, but increasing commercial traffic indicated that it was nearing economic obsolescence.[10] During their first full year in operation in 1938, the locks carried traffic amounting to 1.4 million tons. By 1968 this had spiraled to approximately 41.5 million tons, representing a 454 percent increase in lockages and a 636 percent growth in tonnage. Delays of from 10 to 12 hours were typical and delays of up to 20 hours were not unknown. On one occasion, repair of the main lock held up passages by as much as a week.[11] Anticipated further increases in traffic indicated that a massive overhaul or complete replacement of the facility was necessary.



Locks and Dam No. 26 model

Replacement Locks and Dam No. 26 (Melvin Price)

The Corps, after studying several options, adopted a scheme to build a new structure about two miles downriver from existing Locks and Dam No. 26.[12] Project plans called for construction of two 110-by-1,200-foot locks and a state-of-the-art dam that would provide a navigation pool about 40 miles upstream to Lock and Dam No. 25. At the behest of the St. Louis District, Franco, Glover, and Navigation Branch Chief Louis J. Shows began a lengthy WES model study of navigation conditions that concluded in 1974. Its primary purposes were to ascertain the best location and arrangement of the new locks and lock walls, to determine navigation conditions during construction, and to eliminate any undesirable navigation conditions. The model reproduced a 6.7-mile reach of the Mississippi with the existing Locks and Dam No. 26 on a fixed bed, but with the site of the proposed new locks and dam set in pea gravel that could be rearranged to insert proposed structures and modifications.[13] A simultaneous WES model study supervised by Glenn A. Pickering of the Structures Division dealt with spillway and stilling basin design.[14]


Glenn A. Pickering

By 1974, relying partly on WES model experiments, the Corps had selected a construction site and design criteria for the new edifices. However, one day before the scheduled bid opening on the first major construction contract, 23 plaintiffs filed a lawsuit to stop it. Plaintiffs included 21 railroads opposed to the replacement because it would give barge operators, who paid nothing for use of the Mississippi River waterway, a bigger competitive advantage. Two environmental groups opposed expanding traffic on the Upper Mississippi River due to fears that it would result in detrimental effects to the ecology of the entire region.[15]

The lawsuit delayed the project for nearly five years, during which the Corps conducted further environmental studies and a $15 million test program to determine whether rehabilitation of the existing structures would be less costly but technically acceptable. One study, conducted by Daggett and Thomas D. Ankeny of the WES Mathematical Hydraulics Division, relied on simulation modeling to provide basic information for determining the carrying capacity of proposed replacement locks in conjunction with other locks and dams in the Upper Mississippi River system.[16] Finally, in 1978 Congress and the Carter Administration approved construction of replacement Locks and Dam No. 26, including 1,200 and 600 foot long locks, and required barge owners to pay a fuel tax to defray costs. Construction began in 1979 only after a court trial approved the Corps' Environmental Impact Statement. The main lock opened in 1990. In 1994 the Corps finished the project, renamed the Melvin Price Locks and Dam, at a cost of nearly $1 billion.[17]

Lock Capacity Computer Analysis

Revitalizing the nation's older commercial waterways involved far more than selecting proper lock and dam designs and locations. Even before construction projects got underway, congestion on the Mississippi and Ohio Rivers and in the New Orleans District's section of the Gulf Intracoastal Waterway led WES engineers to develop computer programs for more efficient lock operation and traffic routing. Computerization could not only determine the most effective techniques for operating individual locks, but could trace the impact of individual lock operation through an entire waterway system. Traffic could thus be routed for maximum efficiency within a waterway, speeding flow and preventing delays at locks.

In a first-phase WES study, Daggett and R.W. McCarley of the Mathematical Hydraulics Division analyzed data at Lock and Dam No. 51 on the Ohio River for the purpose of developing a standardized method of sequencing tows waiting in queues.[18] Daggett also adapted LOKDAP, a computer program initially developed by the North Central Division, to simulate traffic in part of the Gulf Intracoastal Waterway.[19] By the mid-1970s,

Daggett, McCarley, and Ankeny had extensively modified and expanded a computer model developed for the Corps at Pennsylvania State University to produce a comprehensive upgrade. The model consisted of two separate computer programs called TOWGEN and WATSIM. Combined, they could simulate the movement of commodities through entire waterway systems, taking into account the characteristics of all tows used in the system and all lock operating characteristics. The Corps used TOWGEN/WATSIM programs extensively to develop traffic routing procedures at Locks and Dam No. 26 on the Mississippi River, the Gallipolis Locks on the Ohio River, and at other locations.[20]

Arkansas River Project

Canalization of the Arkansas River through a huge navigation project exemplified the national enthusiasm for river development in the post-World War II era. Although the Arkansas had not previously been an important commercial artery, political, navigation, flood control, and hydroelectric power interests persuaded Congress to authorize such a project in its 1946 River and Harbor Bill. The river, in fact, had controlling depths during low water periods of only about 2 feet from its mouth to Little Rock, Arkansas, and about 1 foot upriver from Little Rock to the mouth of the Verdigris River in eastern Oklahoma. In some cases, navigation by vessels with 9-foot drafts was impossible for an entire year. To establish and maintain a year-round, 9-foot-deep navigation channel 446 miles up the Arkansas and Verdigris to Catoosa, Oklahoma, would require construction of at least 15 new low-lift lock and dam complexes and one high-lift complex. When work began in the 1950s, the $1.2 billion Arkansas River Project was the largest single civil works program ever taken on by the Corps of Engineers.[21]

The Arkansas River's meandering alluvial regime presented serious engineering problems. Its migrating banks were of erodible materials that caused caving and made an extensive program of bank stabilization, channel regulation, and rectification necessary. The river also carried the third highest sediment load of any river in the United States. Because the Corps had never attempted a major canalization project on a such a stream, sedimentation posed a particularly daunting challenge. Reflecting its concerns in that area, the Corps established a prestigious Arkansas River and Tributaries Sediment Board that included Hans Einstein, Lorenz Straub, and D.C. Bondurant. As the project began, the dam locations and ultimate desired river alignment were not definitely established, and efforts were hindered by the lack of hydrographic surveys available to depict the history of bed configuration changes in various reaches.[22]

Arkansas River model

Even the entrance to the Arkansas River posed a problem. The White River flowed into the Mississippi River a few miles north of the mouth of the Arkansas. However, a natural cutoff developed that connected the Arkansas River with the White River. The 10-mile-long channel stretched from a point 23 miles up the Arkansas River to a point 4.5 miles from the mouth of the White. Part of the flow of the Arkansas then went into the White except when the Mississippi was at high stage; then the flow through the cutoff was reversed. Corps planners decided to use the lower White River as the actual route of navigation into the Arkansas because it afforded a better entrance to the Mississippi River, was reasonably stable, and did not have the sharp bends found in the lower reach of the Arkansas River. Proposals called for traffic to enter the White River from the Mississippi River, move about 9 miles upriver, past the mouth of the Arkansas/White natural cutoff, then through a 10-mile-long manmade canal with a dam and two locks to the Arkansas River. The Arkansas was to be dammed just below the natural cutoff to divert more flows to the White River, and two more manmade cutoffs farther down the Arkansas were under consideration. Construction of this highly complex scheme would produce unknown flow conditions on the lower reaches of the Arkansas River, the White River, the connecting canal, the natural cutoff, and the Mississippi River.[23]

Arkansas River Model Studies

The Station's involvement in the Arkansas River project began in early 1957 when OCE authorized a model study of the Arkansas River entrance. At that time Franco's Waterways Section (Branch after 1963) of the Rivers and Harbors Branch began construction of an outdoor fixed-bed model replete with locks, dams, dikes, railroad fills, and levees, but a reduction in funds soon resulted in a two-year hiatus. Construction did not resume until 1959; experimental work was concluded in 1960. Data notably indicated that, if left unclosed, the Arkansas/White River natural cutoff would continue to develop and increase the movement of sediment into the lower White River. Closure would not only diminish sediment transport into the White River but would benefit navigation by raising stages in the Arkansas River and increasing slope velocities in its lower reach. Accordingly, the Corps adopted a plan calling for closure of the natural cutoff.[24]

WES assumed further Arkansas River responsibilities in 1959 with two movable-bed model studies supervised by Franco. The first was to study general problems of a typical reach of the prototype and to make recommendations relative to channel development and maintenance. By April WES engineers had constructed a model of a representative 11 mile reach of the Arkansas River (between river miles 140.0 and 151.1) with bank and overbank areas of concrete but a bed of sand. No improvements or regulatory structures were included. Designers hoped that the representative-reach model could produce adequate data to predict river behavior in a broad context. However, experiments yielded questionable results because, due to the paucity of data for the Arkansas River, they could not be verified by prototype behavior. Model studies also did "not even roughly approximate the effects of suspended sediment in the river."[25] On a positive note, movable-bed experiments indicated that the use of spur dikes on


Little Rock Reach, Arkansas River model

the concave side of the Arkansas' bends could produce considerable disturbance to flow, reduce channel efficiency, and produce shoaling upstream and downstream.[26]

The second movable-bed model study involved reproduction of a representative 5-mile reach after installation of proposed regulating structures. The reach included one complete bend and portions of upstream and downstream bends curving in the opposite direction of the main bend to form a typical meander pattern. Experiments were to provide information that could be applied generally for the optimal location, design, and operation of a lock and dam on an Arkansas River bend. Designers inserted into the model miniature dikes and a complete lock and dam complex made with sheet metal, Plexiglas, and wood, then conducted a lengthy test series to evaluate several plans of improvement. As in the other Arkansas River movable-bed model study, project engineers hesitated to fully endorse test results because verification was not possible, the model did not simulate the effects of suspended sediment, and many of the problems involved in the design and location of locks and dams in an alluvial river were either not investigated at all or were not completely explored. Sedimentation, the long-time nemesis of many a Corps project and model study, proved yet again elusive to quantify.[27]

Through most of the 1960s the Waterways Branch conducted Arkansas River model investigations to aid in selecting the most advantageous locations, designs, and construction procedures for locks and dams. Unlike the earlier tests that incorporated generic river reaches, the later investigations involved evaluating specific reaches where lock and dam complexes were planned. Also, frustrated by inconclusive movable-bed model tests, WES abandoned the use of movable-bed in favor of fixed-bed models. A study begun in 1961 of a 13-mile river reach for the site of Lock and Dam No. 3 marked the last attempt to use a movable-bed model for the Arkansas River.[28]

A 1964 to 1966 effort to evaluate the hydrodynamic forces in the location of Lock and Dam No. 8, later renamed Toad Suck Ferry Lock and Dam, was typical of the later Arkansas River model studies. A fixed-bed model reproduced a 5.7-mile reach of the Arkansas that extended slightly less than three miles in either direction of a proposed construction site. As in the case of the earlier movable-bed models, a miniature lock and dam complex with guide and guard walls, spillway, piers, and dikes replicated proposed improvements. An electrically-powered model tow and towboat determined the effects of currents on navigation through the lock. Experiments indicated that conditions in the approaches to the lock with the original design would tend to be difficult and hazardous. Recommendations derived from model tests included excavating the right bank above the lock and inserting submerged dikes to reduce current velocities in the lock approach.[29]

Arkansas River Locks

Plans called for the Arkansas River system to incorporate 15, 110-by-600-foot, low-lift locks similar enough so that few design changes would be required at their different sites. In 1962 a Corps conference in Vicksburg, including representatives from OCE and the divisions and districts involved in the Arkansas project, called for a comprehensive model testing program to provide general design criteria for filling and emptying systems in all the river's low-lift locks. This effort paralleled the Station's simultaneous lock standardization and improvement experiments for the Ohio River navigation system.[30]

Because construction of Lock No. 2 in the canal connecting the White River with the Arkansas River was to begin in 1962, Ables and Boyd designed a model reproducing the lock as planned and the channel approaches for about 600 to 700 feet in either direction. Made with simple materials, the model lock chamber was of common plywood and wood with intake manifolds of plastic and sheet metal. Tests of 74 sidewall port arrangements and other factors led to design recommendations incorporated throughout the Arkansas River system.[31] A concurrent test series conducted by R.S. Cummins, Jr., and Grace led to design improvements for spillways and appurtenant structures.[32]

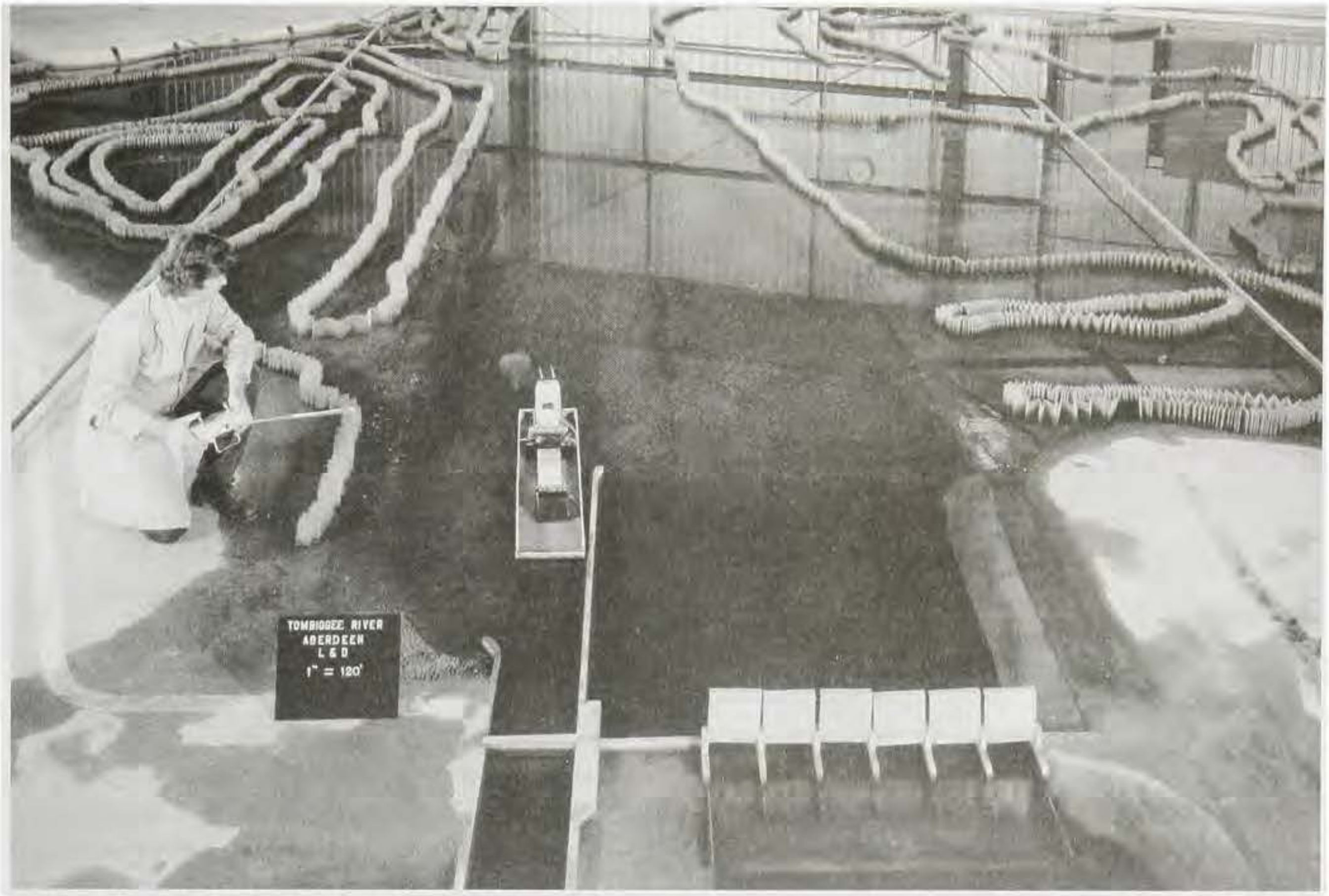

Lock and Dam No. 13 model, Arkansas River

Construction on the Arkansas River project proceeded through the remainder of the 1960s at an impressive pace. Navigation reached Little Rock in December 1968, Fort Smith, Arkansas, in December 1969, and Catoosa, the port of Tulsa, OK, in December 1970. In 1971 Congress named the entire system the McClellan-Kerr Arkansas River Navigation System after two long-serving U.S. senators from Arkansas and Oklahoma, respectively. Although shoaling caused problems in the project's early operation resulting in substantial dredging, within five years the system operated essentially as had been predicted by WES studies, although with limited economic benefits.[36] The Corps later applied WES-developed design criteria for channel stabilization and rectification on the Arkansas River to the highly-sedimented Red River, although with less initial success.[37]

Whereas engineers incorporated standardized design criteria into the Arkansas River's low-lift locks, construction of Dardanelle Lock at river mile 258 marked a clear departure. With a maximum lift of 54 feet, Dardanelle would have by far the highest lift of any lock on the system. As early as 1957 WES began a series of model studies to aid in the design of its approach walls, intakes, and other appurtenances.[33] For actual lock filling, initial planning called for an interlaced bottom lateral system that was never modeled. Instead, WES tests conducted from 1962 to 1964 for the Millers Ferry and Jones Bluff Locks on the Alabama River indicated that the longitudinal floor culvert system developed in France and adapted by Murphy, Boyd, Ables, and others to American conditions was much better than the bottom lateral design for high-lift locks.[34] Ables and Boyd in 1966 and 1967 performed a model study incorporating the WES-developed scheme into Dardanelle Lock. Data again indicated that the longitudinal culvert system resulted in superior performance at a reasonable cost. The Corps then scrapped the original Dardanelle lock filling design and its modifications and adopted the one recommended by WES. Upon completion in 1970 Dardanelle Lock could be filled in slightly more than 8 minutes and emptied in less than 10.[35]

Tennessee-Tombigbee Waterway

Studies for construction of the Tennessee-Tombigbee (Tenn-Tom) Waterway represented another variant in the Station's efforts to improve river navigation. While the Ohio and Mississippi River navigation projects involved revitalization of highly-developed commercial waterways and the Arkansas River venture entailed development of a relatively pristine river system, the Tenn-Tom called for creation of a navigation channel where none existed at all. At the time, it also evolved into the Corps' costliest, most-criticized, and environmentally most-studied project ever.[38]

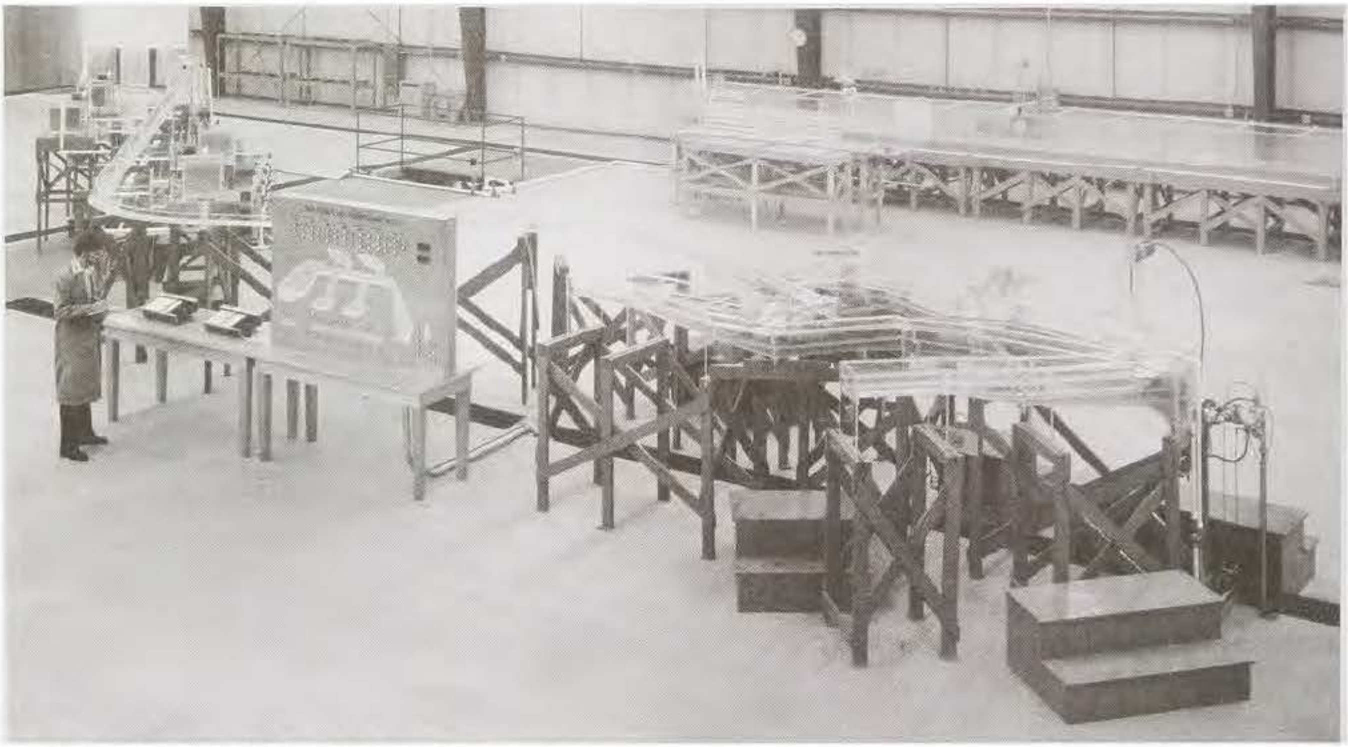


Aberdeen Lock and Dam model, Tenn-Tom Waterway

Running north and south through Mississippi and Alabama, the Tenn-Tom was to connect the Tennessee River on the north to the Tombigbee River on the south. This would shorten by hundreds of miles the barge canal route from the Tennessee River system to the Gulf of Mexico. The huge project had three distinct sections. From south to north a river section involved improving the existing Tombigbee River channel and construction of four conventional locks and dams over a reach of about 173 miles. The central canal section called for cutting a 45-mile canal constructed parallel to the Tombigbee with elevation differences overcome by five locks. Finally, a divide section was to consist of a deep-cut, 40-mile channel through the range of hills separating the Tombigbee and Tennessee drainage areas. It was to include the high-lift Bay Springs Lock and Dam and presented by far the greatest engineering challenges.

Tenn-Tom Tests

The Station's involvement with the proposed waterway extended back to the 1930s when the nascent Soils Division began studies of the canal and divide sections.[39] Activities in the Hydraulics Laboratory began in 1974, two years after the commencement of actual construction. The project called for excavating 300 million cubic yards of earth, one-third more than for the Panama Canal, with most coming from the divide section. To make high rates of earth moving possible, it was necessary to devise methods to keep construction sites as dry as possible. Project engineers from the Nashville District ultimately called for construction of over 100 small hydraulic drainage structures and five major drainage structures in the divide section alone. In 1974 and 1975 Pickering and Ables supervised studies using models of stilling basins and major and minor drainage structures to be incorporated at the construction site. These experiments led to improvements in design, placement, and appurtenant structures.[40] Due partly to a relatively

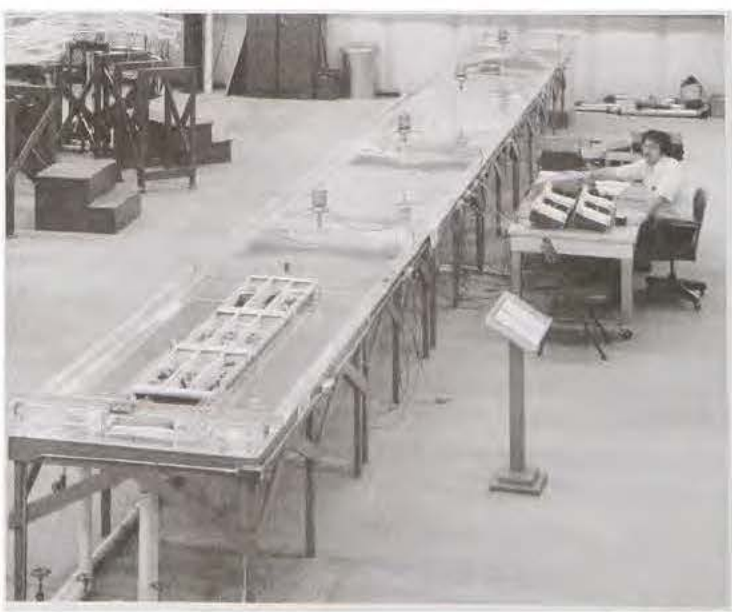


Bay Springs Lake model, Tenn-Tom Waterway

water-free work environment, contractors in one job between 1979 and 1983 moved 100 million cubic yards of earth in just 650 working days.[41]

Further WES involvement concentrated on design and construction of Bay Springs Lock and Dam, the cornerstone of the entire Tenn-Tom system. In what may have been the first WES hydraulics study centered around the environmental sensitivity of a major construction project, the Structures Division used two physical models and one WES-developed numerical model to evaluate water quality within and released from Bay Springs Lake. Water temperatures and dissolved oxygen, factors that especially affect fish, were of paramount concern. One physical model, constructed of transparent plastic to facilitate photography and visual observation, simulated the entire divide cut, Bay Springs Lock and Dam, Bay Springs Lake, four major inflows along the divide-cut canal and the Yellow Creek embayment on Pickwick Lake.[42]

Bay Springs Lock was to have by far the highest lifts on the Tenn-Tom Waterway, ranging from 78 to 92 feet. For it, the Nashville District first adopted a longitudinal floor culvert filling and emptying system based on a design used at New Bankhead Lock on the Black Warrior River in Alabama. Developed by Murphy and Ables at WES, it was typical of the system adapted from French designs and already in use on the Alabama River and at Dardanelle Lock on the Arkansas. As in the final design deliberations for most high-lift locks, however, the Nashville District requested site-specific model tests to determine if modifications were needed. Pickering and Ables drew on experiences derived from earlier high-lift lock model projects to design a



Bay Springs Canal model

plywood lock chamber with sheet metal and plastic appurtenances. Experiments using tows of miniature sheet metal barges, weighted to reproduce desired 9-foot drafts, indicated that the proposed filling and emptying system was effective, but that modifications were needed for valves, floor culvert manifolds and baffling, and outlets in the downstream canal approach.[43] Completed and opened to traffic in 1984, Bay Springs Lock marked the state of the art in high-lift lock design.[44]

Old River Challenges the Corps — Again

In the meantime, activities of the Waterways Division received an unexpected, and highly unwelcome, stimulus from an old nemesis: Old River. The 1963 completion of the massive Old River Control Structure had at least temporarily discouraged the Mississippi River from taking the shorter route to the Gulf of Mexico provided by the Atchafalaya River Basin. For 10 years the facility functioned essentially as the Corps had predicted, although problems arose periodically. In 1964 eight runaway barges slammed into the low-sill structure, forcing operators to close its gates. After removal of the barges, reopening of the gates produced unexpected hydraulic stresses that caused extensive scour damages. The next year a similar accident resulted in more scouring. Diligent control of barge tows prevented further such occurrences, but events had already exposed the structure as far from invincible.[45]

In 1973 the Mississippi River rose to challenge the very survival of the low-sill structure, a key to the Corps' entire Lower Mississippi Valley flood control plan. By mid-March a huge flood pressed between the levees from above Memphis to the Gulf of Mexico. Diversion of only one-fourth of the main stem produced a flow of water six stories deep thundering through the low-sill structure's control gates. In April, as flood waters continued to pour down the Lower Mississippi, a guide wall on the southern inflow (Mississippi River) side began to move, then disappeared. The entire low-sill complex shook noticeably. Even opening the down river Morganza Floodway for the first and only time did little to relieve the pressure.

Old River Low Sill Structure during 1973 Mississippi River flood

South wing wall, Old River Low Sill Control Structure, prior to collapse in 1973 flood

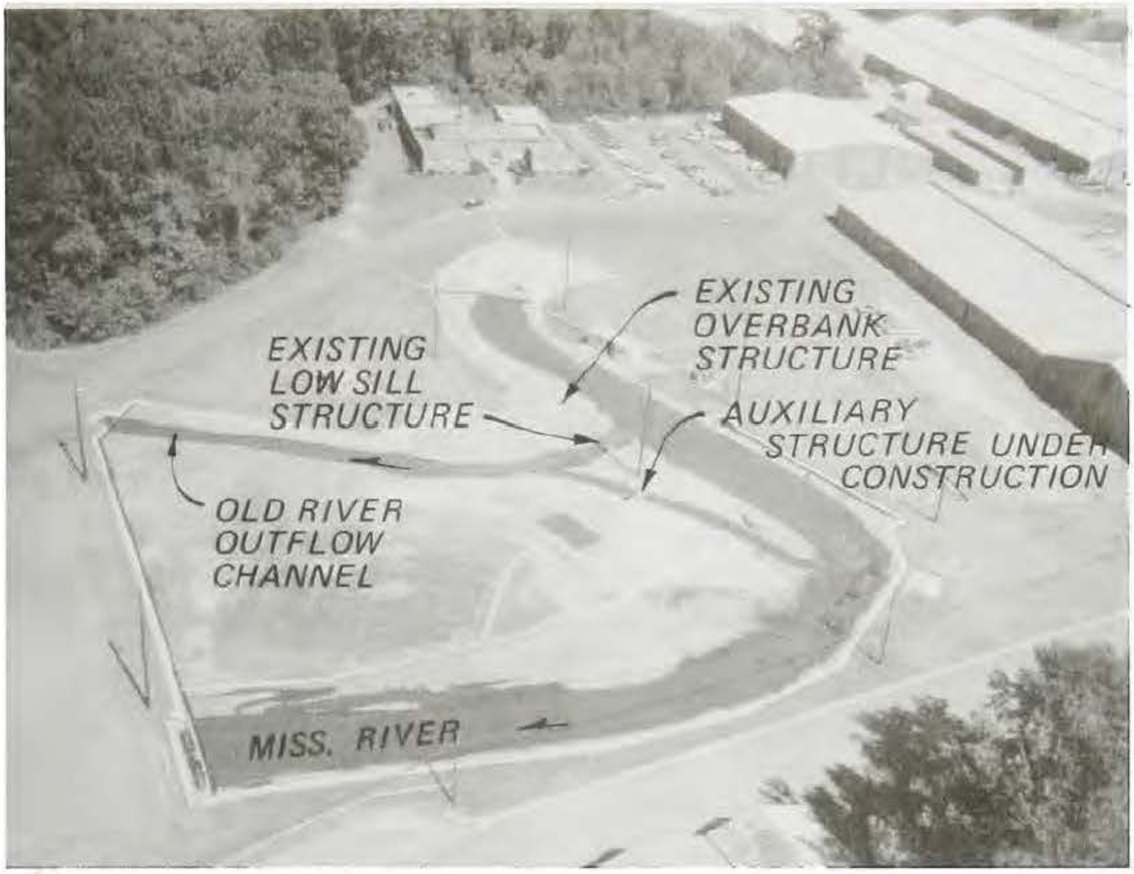
Soundings indicated that a 50-foot-deep scour hole had developed on the inflow side of the low-sill structure, while a hole the size of a small football stadium had formed on the outflow side. With floodwaters preventing more detailed appraisal or control of the damage, the Corps dumped 200,000 tons of riprap into the scour holes, hoping to prevent further harm. Had the scour holes joined, the low-sill structure might well have collapsed and the Mississippi River potentially would flow to the Gulf through the Atchafalaya Basin. The Corps, as well as millions of inhabitants of the Lower Mississippi River Valley, faced an enormous crisis.[46]

Although the low-sill structure held, post-flood investigations revealed extensive damage. When the Corps drilled holes down through the concrete dam with special diamond-tipped bits and lowered a television camera, the first thing the Lower Mississippi Valley Division Engineer saw was fish where there should have been solid foundation.[47] One Corps document stated that the foundation under approximately half of the low-sill structure had been "drastically and irrevocably" changed.[48]

New Old River Model Studies

WES involvement began inauspiciously at the height of the flood. Simmons received a telephone call informing him of the collapse of the low-sill structure's guide wall and requesting that WES send representatives to an onsite conference as soon as possible. The next day Simmons, John Franco, Thomas Murphy, and Fred Brown left Vicksburg in a small plane. Upon arriving at the Old River complex, their pilot missed the muddy landing strip, hitting parallel to it in high grass that concealed about 4 inches of water. The group hydroplaned out of control before stopping just short of a herd of cows. Adding abject fright to an already tense condition, Simmons noted of their close call that "You haven't lived until you land a small plane in a situation like that."[49]

Upon returning to the Station, the WES contingent quickly mobilized almost the entire Waterways Division to design and build a model for immediate and long-term tests. By August 1973, only four months after the flood's crest, the Division had supervised construction of an undistorted fixed-bed model that reproduced



Old River outdoor model constructed in 1973

approximately a 15-mile stretch of the Mississippi River, the low-sill and overbank control structures, and about five miles of the Old River outflow channel. Built outdoors because there were no hangar facilities available, the new model covered approximately 1.5 acres in front of the Hydraulics Laboratory's administrative building. It could replicate one hour of prototype activity in 5.5 minutes and required 7,700 gallons of water per minute to operate. WES crews at first ran the model six days a week for a period of 6 to 8 months, often at night to avoid interference from daytime winds.[50]

Experiments conducted in the fixed-bed model from 1973 to 1977, supervised by new Waterways Division Chief J.E. Glover and performed primarily by B.K. Melton, Pokrefke, and C.R. Nickles, concentrated on determining means of repairing damage to the low-sill structure and preventing future conditions that could endanger its stability. Factors considered included flow conditions during rehabilitation of damage to the stilling basin, the need for additional scour protection in the outflow channel below the stilling basin, a means of controlling the tailwater of the low-sill structure, and replacing the failed left wing wall with a rock structure.[51]

In 1975 the Division constructed a complementary indoor distorted movable-bed model with a bed of crushed coal. Personnel used it to investigate remedial measures to stabilize the Mississippi River channel, to develop plans for improving alignment of currents approaching the low-sill structure, and to evaluate the impact of proposed repair and construction plans on sediment distribution.

While the Waterways Division experimented with its large-scale physical models, the Structures Division designed and built two section models in a glass-sided flume, one to simulate the three low gate bays in the center of the low-sill structure,

J. E. Glover

Low Sill Control Structure, Old River outdoor model (showing wing wall intact)

the other to simulate the eight flanking high gate bays. Working in concert with tests in the fixed-bed and movable-bed models, project engineer Edward D. Rothwell evaluated performance of the low-sill structure's gate bays and their method of operation. These tests indicated that substantial changes in the method of operating the low-sill gates would be necessary to achieve desired flow distributions without creating adverse hydraulic conditions. Model results specifically revealed that closing one gate bay while leaving adjacent gates open induced severe turbulence upstream from the closed gate. Thereafter, the method of regulating flows through the low-sill structure by fully closing various gate bays was discontinued.[52] Bobby P. Fletcher, using the same models, supervised a test series to develop guidelines for rehabilitating the existing stilling basin and to evaluate characteristics of debris passage through the structure.[53] A third Hydraulic Structures Division effort conducted by Ronald R. Copeland in 1979 used a model of the Old River overbank structure to evaluate several plans of improvement.[54]

Auxiliary Control Structure

Despite major efforts to repair, restore, and improve conditions at the low-sill structure, its capacity to control flows into the outlet channel during times of flooding was permanently and seriously reduced. Whereas the structure was designed to operate with a maximum head of 37 feet (the difference between the water levels of the inflow and outflow channels), by the late 1970s this had been reduced to 20 feet.[55] Corps leaders saw the necessity of an auxiliary control structure if the Mississippi River was to be contained in its present channel.

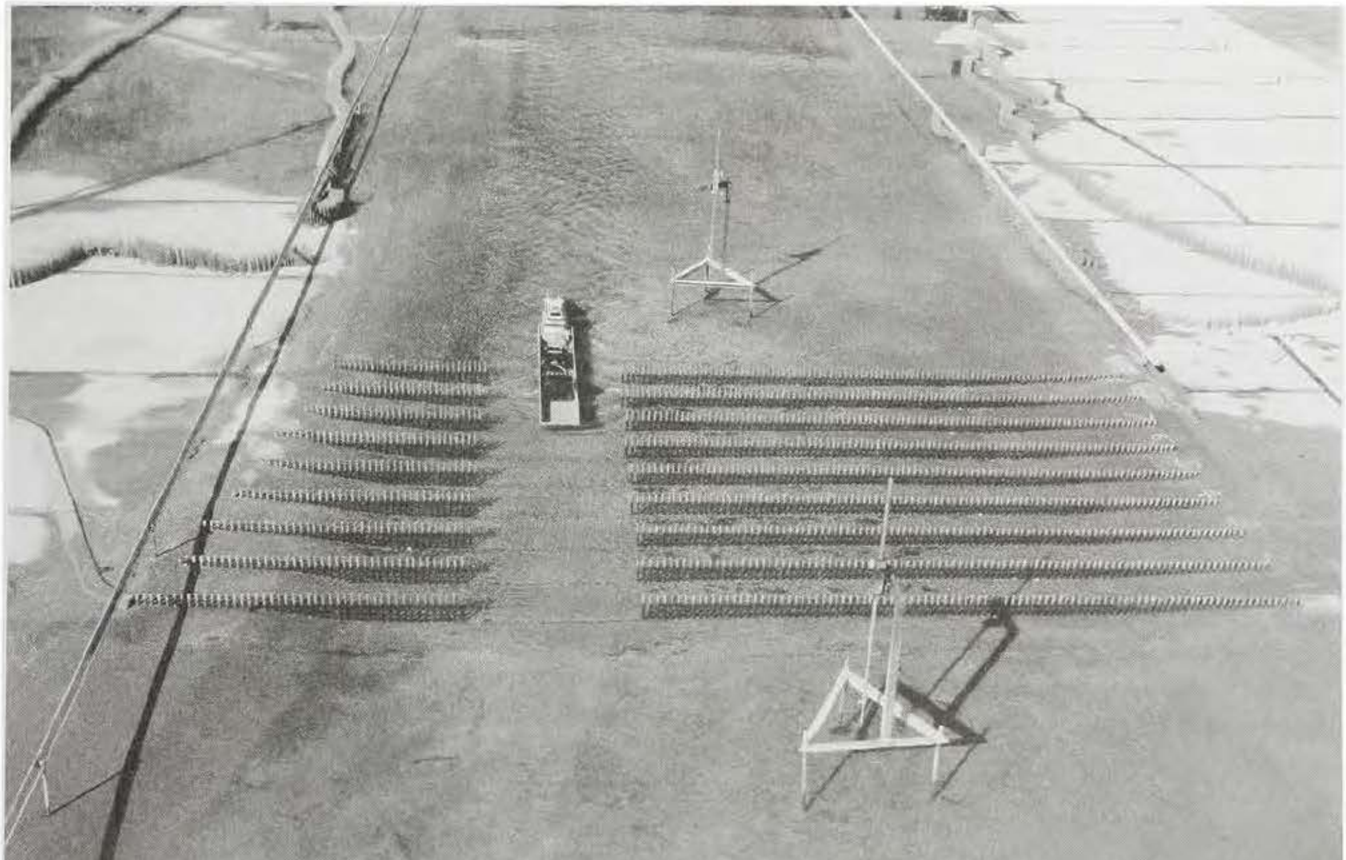
Old River Diversion Structures indoor (moveable bed) model

By 1977 the Corps had adopted plans for an auxiliary control structure and inflow channel just downriver from the existing low-sill structure. WES engineers modified the movable-bed model to include the proposed structure and channel, then conducted a test series in 1977 and 1978 to evaluate possible hydrodynamic changes and sediment transport. The Structures Division next designed two smaller models of the auxiliary structure with relatively short stretches of the approach and discharge

channels. Under the direction of Fletcher and P. Bhramayana, personnel used one to investigate and evaluate designs to provide satisfactory flow characteristics in the approach channel, at the abutments, over the spillway, in the stilling basin, and in the exit channel. The second model was used to determine the magnitude and frequency of hydrodynamic loads acting on the structure itself, especially its gates, providing data for optimal design and operation.[56]

Flume study of stilling basin performances, Old River Overbank Structure

After extensive model tests and design revisions, the Corps began construction of the auxiliary structure in 1981. Its inflow channel split from the Mississippi River about two miles below that of the low-sill structure, led to the new auxiliary structure, then angled into the existing outflow channel a short distance below the low-sill structure. Completed in 1986, it cost more than three times as much as its low-sill predecessor.



Outflow channel, Old River outdoor model

Ohio River Flood Flows

Numerical modeling of flood flows marked an exception to the dominance of physical modeling in river engineering through the 1970s. Long before the computer revolution, the Ohio River Division had been interested in the development of numerical models to aid in its flood control mission. The reach of the Ohio River stretching from Louisville downstream to the confluence of the Ohio River and the Mississippi River at Cairo was of special concern. In that stretch of about 365 river miles, four major tributaries — the Green, Wabash, Cumberland, and Tennessee Rivers — flowed into the Ohio along with several lesser streams. The Tennessee met the Ohio about 50 river miles up the Ohio from Cairo, with the Cumberland flowing into the Ohio only about 10 miles farther upstream. Both the Tennessee and Cumberland Rivers provided large inflows into the Ohio, which was in turn by far the largest tributary of the Mississippi. Thus, four major North American rivers — the Ohio, Cumberland, Tennessee, and Mississippi — converged and interacted in a small geographical area. The routing of floodwaters on the lower Ohio and its tributaries, especially the Cumberland and Tennessee, affected not only the lower Ohio River Valley, but was crucial to flood control efforts on the Lower Mississippi River.

As the agency responsible for routing flows on the Ohio River, the Ohio River Division during times of flooding directed the operation of huge TVA flood control reservoirs on the Cumberland and Tennessee Rivers located near their junctions with the Ohio River. Proper control of flows from Barkley Reservoir on the Cumberland and Kentucky Reservoir on the Tennessee was vital to the regulation of levels on the Ohio. The Division also operated five high-lift lock and dam complexes on the Ohio between the mouth of the Cumberland and Louisville. These not only provided for commercial navigation on the Ohio, but were used to impound and release waters to control river levels.

Numerical Modeling of Flood Flows: SOCHMJ and FLOWSED

In 1953 the Ohio River Division had contracted J.J. Stoker of New York University to develop computer programs capable of expressing unsteady flows such as those found in a river. Stoker subsequently devised an explicit finite difference scheme that theoretically could be applied to flood water routing. Despite the Division's early interest in computer programs and Stoker's innovative theories, numerical modeling of floodwater routing was not then applied to the Ohio River system. Instead, by the late 1960s TVA engineers incorporated Stoker's explicit finite difference concept into two computer models for use on the Tennessee River. The first, entitled Simulated Open Channel Hydraulics (SOCH), was capable of mathematically expressing flows in open channels only when tributaries could be handled as lateral inflows to the main channel. An improved version, called Simulated Open Channel Hydraulic Junction (SOCHJ), could handle one tributary (one "junction") in addition to the main channel in unsteady-flow computations.[57]

The TVA-developed programs caught the attention of Ohio River Division engineers and the Mississippi Basin Model Board. In 1970 the Model Board authorized a study to develop computer programs for unsteady-flow computations along reaches of the Mississippi River and some of its larger tributaries. In January of the following year the Model Board, in a joint venture with the Ohio River Division, gave WES the responsibility of developing a numerical model to calculate flows on the Ohio River in the stretch from Louisville to Cairo and of producing a computerized flood routing program for the Division.[58]

By December 1972 Billy Johnson of the Mathematical Hydraulics Division had applied SOCH to study a hypothetical flood wave traversing the Ohio River from Louisville to Rosiclare, Illinois, about 80 river miles upriver from Cairo. Johnson had joined WES only the year before, and despite holding a doctoral degree in aerospace engineering with a minor in mathematics, he had little computer training. A

rigorous program of on-the-job training, diligence, and guidance from Keulegan quickly led him to become an expert in numerical modeling.[59] Because SOCH could treat tributaries only as lateral flows, it could not be accurately applied to the downriver stretch, where both the Cumberland and Tennessee Rivers joined the Ohio, or where the Ohio flowed into the Mississippi. Below Rosiclare, Johnson applied the upgraded SOCHJ program in attempts to calculate the impact of flows from the Cumberland and Tennessee into the Ohio, then to determine the effects of flows from the Ohio into the Mississippi. Although verification data obtained from the MBM indicated a high degree of accuracy in many areas, neither SOCH or SOCHJ could adequately predict stages produced by releases from the Barkley and Kentucky Reservoirs. To do so required a much more complex numerical model capable of treating the Cumberland and Tennessee Rivers as dynamic branches of an integrated system rather than as lateral flows or a single tributary.[60]

By early 1974, in a second-phase study funded by the Ohio River Division, Johnson had made extensive modifications to the existing computer program to produce a version called Simulation of Open Channel Hydraulics in Multi-Junction Systems (SOCHMJ). It could be applied to a river system composed of any number of junctions and branches. This was necessary for the highly complex Ohio-Cumberland-Tennessee-Mississippi area with its three junctions and seven branches, all of which had to be included in calculations to determine the effects of releases from the Barkley and Kentucky Reservoirs. Projections from SOCHMJ, when compared with field data obtained from reservoir releases during the huge flood of 1973, produced excellent agreement. Application of the SOCHMJ numerical model then provided the Ohio River Division with an accurate tool to plan reservoir releases and to predict their impact on flow stages throughout the region. Beginning in late 1974 the Ohio River Division used the model on a daily basis to make forecasts at Cairo as well as at other points along the lower Ohio and the Mississippi River.[61]

The successful application of SOCHMJ, especially as an aid in determining the operation of Barkley and Kentucky Reservoirs during periods of flooding, encouraged the Ohio River Division to extend the model's limits upriver to McAlpine Lock and Dam, with the Green and Wabash Rivers treated as dynamic branches of the system. Johnson then expanded SOCHMJ capabilities to handle computations for high-lift locks and dams at Cannelton, Newburgh, and Uniontown, downriver from McAlpine Lock and Dam. The model then simulated approximately 750 river miles and replicated a prototype area with six major rivers (the four in the original application plus the Green and Wabash), 12 junctions, 18 branches, 15 local inflows, and five high-lift locks and dams.[62]

By 1978 the Ohio River Division expressed an interest in developing a modeling capability for the complete Ohio River, from Pittsburgh to Cairo. Due to certain limitations and cost considerations, use of SOCHMJ was not feasible. Johnson consequently chose a model developed by H.S. Chen at MIT for use on the upper Mississippi River as the base from which an Ohio River model could be devised. Necessary modifications included generalization of the basic program to handle a system with an unlimited number of branches and junctions, and, most important, the incorporation of a technique similar to that programmed in SOCHMJ to handle the many high-lift locks and dams in the system. The resulting program was called FLOWSED because it included both flow and sediment calculations. By 1981 Johnson had applied FLOWSED the entire length of the Ohio to the juncture of the Allegheny and Monongahela Rivers. Sediment computations were later eliminated, but the name FLOWSED stuck.[63]

Notes

1. The original canalization project called for construction of 54 locks and dams. Elimination of eight proposed structures reduced the number to 46. Confusion results because most locks and dams were numbered before the elimination of the eight proposed complexes. Thus Lock and Dam No. 53, near the confluence of the Ohio and Mississippi Rivers, is actually the 46th structure in the system. See Leland R. Johnson, *The Falls City Engineers: A History of the Louisville District, Corps of Engineers, United States Army* (Louisville: U.S. Army Corps of Engineers, 1974), 227.

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3. Johnson, *Falls City Engineers*, 233; and Robinson, *History of Navigation*, 39.

4. "Navigation Conditions at Markland Locks and Dam, Ohio River, Hydraulic Model Investigation," WES *Technical Report No. 2-446* (Vicksburg: WES, 1957); and "Navigation Conditions at Greenup Locks and Dam, Ohio River, Hydraulic Model Investigation," WES *Technical Report No. 2-469* (Vicksburg: WES, 1958).

5. John J. Franco and Cody D. McKellar, "Navigation Conditions at Cannelton Locks and Dam, Ohio River, Hydraulic Model Investigation," WES *Technical Report H-75-6* (Vicksburg: WES, 1975); Louis J. Shows and John J. Franco, "Navigation Conditions at Uniontown Locks and Dam, Ohio River, Hydraulic Model Investigation," WES *Technical Report H-75-9* (Vicksburg: WES, 1975); Louis J. Shows and John J. Franco, "Navigation Conditions at Lock and Dam 53, Ohio River, Kentucky and Illinois, Hydraulic Model Investigation," WES *Technical Report HL-79-14* (Vicksburg: WES, 1979); Louis J. Shows and John J. Franco, "Navigation Conditions at McAlpine Locks and Dam, Ohio River, Hydraulic Model Investigation," WES *Technical Report HL-81-7* (Vicksburg: WES, 1981); John J. Franco and Thomas J. Pokrefke, Jr., "Smithland Locks and Dam, Ohio River, Hydraulic Model Investigation," WES *Technical Report HL-83-19* (Vicksburg: WES, 1983); and L.J. Shows and R.T. Wooley, "Navigation Conditions at Gallipolis Locks and Dam, Ohio River, Hydraulic Model Investigation," WES *Technical Report HL-89-10* (Vicksburg: WES, 1989).

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7. Ibid.

8. See Edwin R. Decker, "Replacement — Lock and Dam No. 26: History, Objectives and Scope," *American Society of Civil Engineers: Journal of the Waterways and Harbors Division* 96 (1970), No. WW1: 1-8.

9. *Final Report. Laboratory Tests on Hydraulic Models of Lock and Dam No. 26, Mississippi River, Alton, Illinois. Tests made for U.S. Engineer Office, St. Louis, Missouri* (Iowa City, Iowa: U.S. Engineer Sub-Office, Hydraulic Laboratory, 1937).

10. Daniel P. Marshall, Jr., "Replacement — Lock and Dam No. 26: Condition of Existing Structure," *American Society of Civil Engineers: Journal of the Waterways and Harbors Division* 96 (1970), WW1: 27-47.

11. Decker, "Replacement — Lock and Dam No. 26," 5.

12. Richard C. Armstrong, "Replacement — Lock and Dam No. 26: Plans Considered," *American Society of Civil Engineers: Journal of the Waterways and Harbors Division* 96 (1970), WW1: 49-64.

13. Louis J. Shows and John J. Franco, "Navigation Conditions at Locks and Dam 26, Mississippi River, Hydraulic Model Investigation," WES *Technical Report HL-79-19* (Vicksburg: WES, 1979).

14. N.R. Oswalt and G.A. Pickering, "Spillway for Lock and Dam 26, Mississippi River, Missouri and Illinois, Hydraulic Model Investigation," WES *Technical Report H-73-15* (Vicksburg: WES, 1973).

15. See "Barge Bottleneck Uncorked," *Civil Engineering* 39 (1987): 38-41.

16. Larry L. Daggett and Thomas D. Ankeny, "Determination of Lock Capacities Using Simulation Modeling," WES *Miscellaneous Paper H-75-9* (Vicksburg: WES, 1975).

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22. Ibid. Also see *Arkansas River Channel Model Study, Model Adjustment, Interim Report 1* (Vicksburg: WES, 1959).

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24. Ibid.; and *Arkansas River and Tributaries, Arkansas and Oklahoma, White River Entrance Channel, Mississippi River to Arkansas Post Canal, Design Memorandum No. 1, General* (Little Rock: U.S. Army Engineer District, Little Rock, 1964).

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29. J.J. Franco and L.J. Shows, "Navigation Conditions at Lock and Dam No. 9, Arkansas River, Hydraulic Model Investigation" WES *Technical Report No. 2-817* (Vicksburg: WES, 1968). The model test program resulted in publication of a lengthy series of *Technical Reports* dealing with individual lock and dam sites.

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45. Reuss, *Designing the Bayous: The Control of Water in the Atchafalaya Basin*, 52.

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48. Cited in McPhee, *Control of Nature*, 49.

49. Henry B. Simmons interview.

50. Thomas J. Pokrefke, interview by author, Vicksburg, 3 June 1996. J.J. Franco and C.R. Nickles prepared a draft including a detailed description of the model as "Old River Diversion, Mississippi River; Report 1, Introduction, Description, Adjustment and Verification of Models, and Summary of Results," that was not published.

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9 Current Trends and New Directions, 1983-2004

Approaching the New Millennium

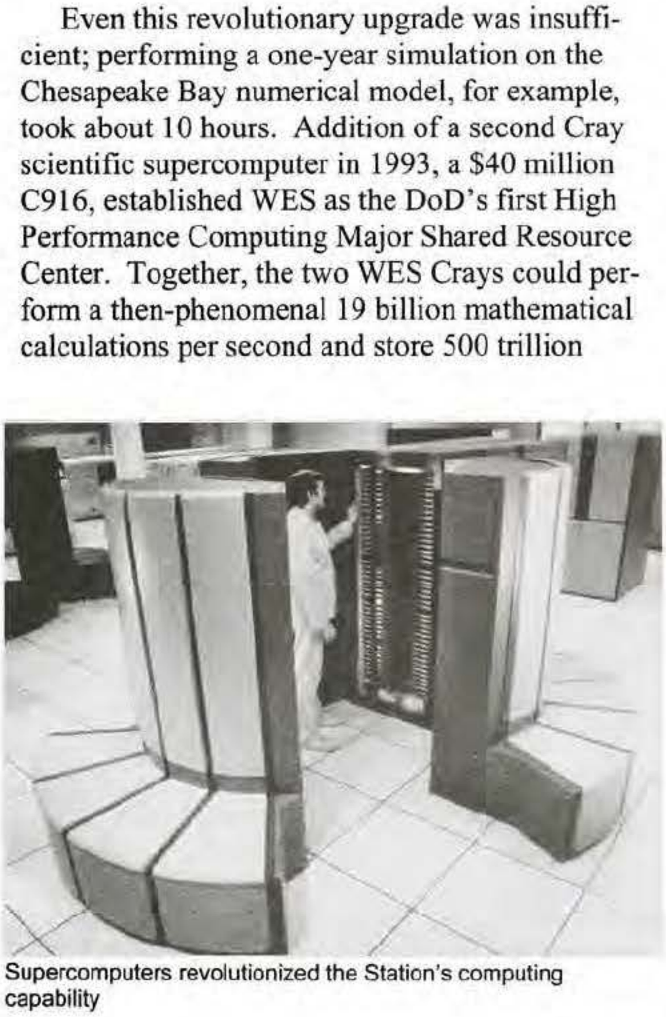
As WES conducted its sixth and seventh decades of research, activities of the Hydraulics Laboratory reflected several trends:

- greatly expanded use of computers in all research activities, especially through an enhanced in-house computer capability,
- development of highly complex two- and three-dimensional numerical models of rivers and estuaries,
- an enlarged role in ship channel design and improvement through development of a computerized ship navigation simulator,
- continued use of physical models for design of hydraulic structures, river engineering, and flood control,
- increased environmental concerns in areas such as salmon migration in the Pacific Northwest and erosion control, and
- military hydrology studies.

Computer Upgrades

Only a greatly expanded in-house computer capability enabled WES engineers to develop the complex two- and three-dimensional computer programs necessary for hydraulic modeling by the late 1980s. Recognizing the integral role computerization would play in future engineering, WES in 1986 established a separate Information Technology Laboratory (ITL) to expand and centralize computer capabilities. Due largely to efforts by Whalin, in 1989 the Department of Defense chose the WES ITL as one of only four sites for its major supercomputer centers. WES then quickly acquired a $27.5 million Cray Y-MP scientific supercomputer with capabilities dwarfing those of previous WES equipment.

Even this revolutionary upgrade was insufficient; performing a one-year simulation on the Chesapeake Bay numerical model, for example, took about 10 hours. Addition of a second Cray scientific supercomputer in 1993, a $40 million C916, established WES as the DoD's first High Performance Computing Major Shared Resource Center. Together, the two WES Crays could perform a then-phenomenal 19 billion mathematical calculations per second and store 500 trillion



Supercomputers revolutionized the Station's computing capability

characters of information. Further upgrades and additions, beginning with a $202 million contract in FY 1996, made ITL the preeminent engineering information technology laboratory in DoD. In 1999 ITL mainframe computers were capable of performing 1.4 trillion functions per second.

Computer capabilities increased not only through the establishment and development of ITL, but also through new and upgraded equipment within the Hydraulics Laboratory. By the early 1980s a few engineers had personal computers (PCs) in their offices, even before the invention of the DOS operating system. Although one HL administrator warned that he did not want to see his "engineers converted to typists," by the mid 1980s the laboratory had set a goal of a computer for every office. On the assumption that it was preferable for every engineer to have some type of computer – even one with very limited capabilities – than for a few to have the state of the art, the lab first purchased cheaper two-floppy-drive models. By the late 1980s hard drive models had become standard, and to most engineers the PC had become an indispensable tool. While PC capabilities increased geometrically in the 1990s and prices declined, the laboratory invested heavily in maintaining its engineers at the cutting edge of the new technology. By the late 1990s every HL engineer's office had at least one state-of-the-art PC, with multiple models the norm. The computer revolution triumphant, the average engineer then had more computing power at his fingertips than the entire WES mainframe system of a generation earlier.[1]

New Facilities

By the 1980s Hydraulics Lab administrators and engineers faced a serious shortage of comfortable and convenient office space. Engineers and their research groups were widely scattered over the WES reservation, some in non-air conditioned hangers. Finally, in 1986 the Station began construction of a new HL headquarters and office facility that was completed in 1987. At a cost of $3 million, the project included renovation of two existing buildings and connecting them with a new structure. The 35,321-square-foot (22,743 square foot new) building then served as laboratory headquarters with 135 offices, a computerized ship simulator, and conference and classroom facilities.

Hydraulics Laboratory headquarters dedication April 26, 1988; (from left) Bill Fenwick, HL engineer and son of Brad Fenwick; a construction representative; Henry Simmons, retired chief of the Hydraulics Laboratory; Colonel Dwayne Lee, Commander of the Waterways Experiment Station; Gerald McKenzie, WES construction inspector; Robert Whalin, Technical Director; Garbis Keulegan; Frank Herrmann, Chief of the Hydraulics Laboratory

New Hydraulics Laboratory headquarters, 1987

TABS-2: Numerical Modeling Triumph

By the mid-1980s, even before the Station's acquisition of supercomputers, WES engineers had pushed numerical modeling to new limits in almost every realm of the Station's hydraulics mission. Thomas and McAnally, for example, spearheaded efforts to develop a two-dimensional (2-D) program capable of simulating hydrodynamic factors and sedimentation in highly complex estuary, harbor, reservoir, or inland waterway systems. By refining and combining existing programs they produced an integrated model — dubbed TABS-2 — that by the mid-1990s had been applied to over 50 Corps studies. (Laboratory legend has it that TABS was an acronym for the Tony Thomas And Bill McAnally System. However, both McAnally and Thomas insist that the name grew out of the tabbed notebook used to hold input instruction.)

Development of TABS-2 evolved partly out of hybrid modeling of the Columbia River estuary in the late 1970s. At that time McAnally, Thomas, and Ariathurai had produced an upgraded sedimentation model called STUDH. That model predicted shoaling in the Columbia estuary even more accurately than its creators had hoped. Further advances, accomplished primarily by McAnally and Thomas, integrated STUDH with two other computer models, RMA-2V and RMA-4, and led to the invention of over 40 complementary utility programs, resulting in a TABS-2 prototype. Improvements in computer graphics greatly enhanced the venture.[2]

Early TABS-2 applications by the St. Louis and Vicksburg Districts effectively simulated erosion and deposition at Lock and Dam No. 26 and in the Greenville Reach on the Mississippi River. By 1984, in subsequent investigations, the Corps had applied TABS-2 to such widespread projects areas as the Yazoo River backwater, Lock and Dam No. 2 on the Red River, New York Harbor, and Corpus Christi Bay.[3] By 1985 demand for TABS-2 projections led Thomas and McAnally to publish a lengthy *User's Manual* for use by Corps divisions and districts. Still, TABS-2 faced by far its most difficult challenges when applied to investigations of Louisiana's developing Atchafalaya River delta and to sedimentation problems on the Red River.

The Growing Atchafalaya Delta

The opening of the Old River Control Complex in 1963 substantially increased the load of sediment carried by the Atchafalaya River.[4] Progressively, this sediment filled in the Atchafalaya basin floodway between its natural and manmade levee systems, then causing the Atchafalaya to carry much of its sediment load all the way to Atchafalaya Bay on the Gulf of Mexico. There, sediment began to build rapidly growing deltas at the river's two mouths. While most of the Louisiana coast was experiencing land loss, by the early 1970s the development of the Atchafalaya deltas

had converted shallow bays into densely vegetated marshes. Deltaic growth after 1972 accelerated phenomenally, creating new marshes, altering existing wetland habitats, modifying the water quality of Atchafalaya Bay, affecting flood flow lines, and increasing the need for dredging. Enclosing one of the most dynamic delta-building systems in the world, Atchafalaya Bay then presented a unique, albeit troublesome, opportunity to study deltaic processes.[5]

As the agency responsible for flood control and navigation in the Atchafalaya River basin, the New Orleans District charted changes in Atchafalaya Bay with a degree of alarm. Because almost no data existed pertaining to developing deltas, the Corps could not make long-term predictions for the Atchafalaya Bay complex and the district could not adequately plan to perform its missions there. Faced with this unusual problem, in 1976 the New Orleans District hosted a symposium on "Predicting the Evolution of Atchafalaya Bay." There the District sought assistance from WES, represented by Boyd, inquiring specifically as to whether WES could develop a numerical model to calculate long-term delta formation.[6]

According to McAnally, the WES reaction was at first discouraging. Such deltaic projections had never been attempted by the Corps, and many considered an adequate computer model to be beyond the state of the art. Although McAnally and others were successfully applying the STUDH numerical model to sedimentation studies of the Columbia River, the Columbia's sediment load was almost entirely sand while the Atchafalaya carried a mixed load of sands, silts, and clays. Conditions in Atchafalaya Bay also involved river currents, winds, barge movements, tides, and waves. Nonetheless, McAnally claimed to be "too aggressive and too dumb" to be scared of the project.[7] In 1977 he and Thomas, assisted by others from WES and later by a group of consultants that included Ray Krone, began collecting prototype data to develop a numerical model of Atchafalaya Bay. Their efforts eventually transcended all previous sedimentation-related modeling ventures.[8]

The multi-year, multi-million-dollar Atchafalaya project eventually led to the incorporation of a number of existing or modified computer models into an integrated system. Project engineers first used Johnson's SOCHMJ model to calculate the Atchafalaya's flood stages and flow distributions that had changed as the result of delta growth. (Johnson had previously used SOCHMJ to predict flood flows on the Ohio River.) In subsequent attempts to compute sediment transport, deposition, and erosion in the bay, WES researchers made substantial modifications to an existing one-dimensional sedimentation program called HEC-6. Thomas had originally developed this program at the Corps' Little Rock District before refining it at the Hydrologic Engineering Center in California.[9] The new WES upgrade, called HAD-1, was a quasi-two-dimensional numerical model capable of simulating sedimentation processes caused by a river flowing into a quiescent bay.[10]

The crowning accomplishment of the Atchafalaya Bay project, however, was the further maturation and application of TABS-2. According to McAnally, by 1989 Joe V. Letter and Barbara P. Donnell used the model to reproduce "eerily accurate" delta growth in the Louisiana prototype.[11] TABS-2 could not only replicate the bay's historical evolution, but could project deltaic development up to 50 years into the future for a multitude of scenarios. Application of TABS-2 paid immediate dividends when the New Orleans District used model projections to revise levee construction in the Avoca Island area of the Atchafalaya Floodway, saving $180 million over an original design proposal.[12]

Joe V. Letter

Barbara P. Donnell

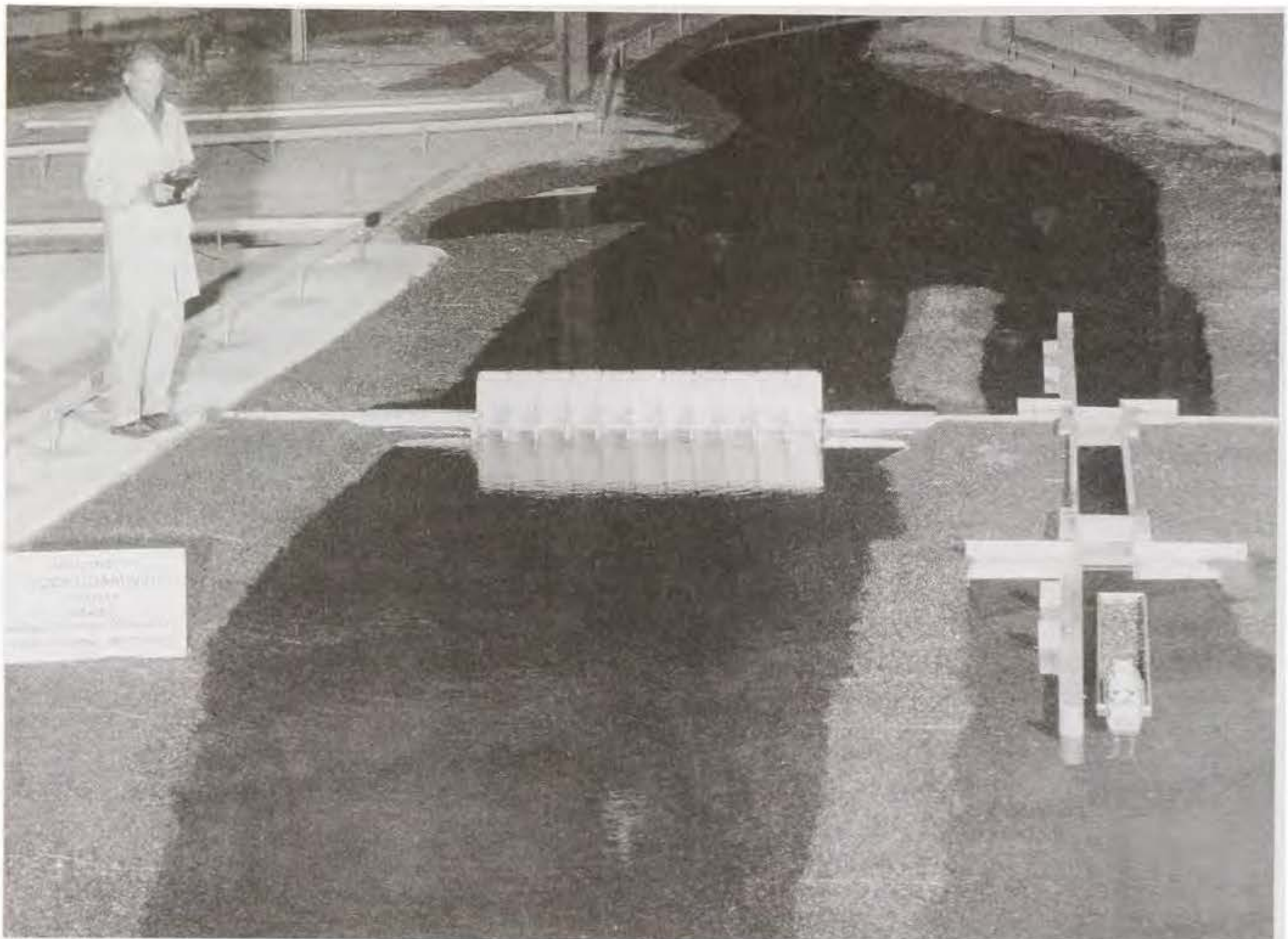
Red River: Sedimentation Nightmare

Application of TABS-2 to sedimentation studies on the Red River paralleled its successful use in the Atchafalaya delta. Authorized by Congress in 1968, the massive Red River Waterway Project represented the Corps of Engineers' last great western river canalization enterprise. It was to provide a 200-foot-wide, 9-foot-deep navigation channel from the Old River/Mississippi River junction up the Red River to Shreveport, LA. Plans called for construction of five lock and dam complexes that were to be coordinated with other river improvements.[13]

Like the Arkansas River, the lower Red River was alluvial, flood prone, meandering, and highly sedimented, extensive channel realignment and bank stabilization works were necessary. In 1971, shortly after Congress provided start-up funds, the New Orleans District requested WES model studies to identify the most effective types of dikes to improve the channel of the Red and to develop criteria for cutoff construction. Drawing on experiences from the recently-completed Arkansas River studies, Franco supervised design of a movable-bed model reproducing 10 miles of a typical troublesome river reach. The prototype reach would require channel realignment, considerable channel training and stabilization structures, and possibly a bend cutoff. Diverging from most previous river-reach studies, project technicians built the model in a large flume that could be converted to examine other river reaches as required. Banks and overbank areas were of loose gravel to facilitate changes, while crushed coal formed the bed of the model. Rows of metal rods and crushed stone reproduced pile dikes and stone dikes, respectively. Experiments continued until 1976.[14] A concurrent movable-bed test series, completed in 1978, analyzed potential channel development of the lower reach of the Red River and its junction with Black River.[15]

Red River movable-bed model

Another WES project conducted from 1972 to 1978 focused on Red River Lock and Dam No. 1 (later named Lindy C. Boggs Lock and Dam). To be located in a cutoff channel about 44 miles above the Mississippi River and 9.5 miles above the confluence of the Red and Black Rivers, design and construction of the complex could serve as a model for the other structures in the system. WES engineers resorted to multiple model experiments to evaluate various characteristics of the prototype area and of the structures themselves. The Waterways Division designed a conventional physical model that could be used for both fixed-bed and movable-bed tests. Fixed-bed tests simulated navigation conditions in the vicinity of the lock, while movable-bed experiments attempted to predict shoaling and sedimentation resulting from construction and channel realignment. Also, spillway models furnished data to evaluate the stilling basin, riprap, and other structural features of the project.[16]


Lock and Dam No. 1, Red River model

After completion of the facility in the fall of 1984, operation of Lock and Dam No. 1 was near-disastrous. Deposition of fine sediment in the upstream and downstream lock approach channels was much greater than anticipated, and material deposited against the lock gates fell into the lock chamber when the gates were opened. Eventually the lock had to be closed, dewatered, and cleaned out, suspending traffic on the Red River for three months. The costly calamity led to a rapid succession of WES model studies intended to evaluate proposed remedial measures for Lock and Dam No. 1 and to prevent such occurrences at the other four planned Red River complexes. These studies made extensive use of numerical models to interpret sediment-related factors in a complex river regime for the first time.[17]

Red River Hybrid Studies

In 1984 and 1985 Copeland and Thomas applied two numerical models to a study of the Lock and Dam No. 1 vicinity, one to evaluate the effect of contraction works on the navigation channel, the other to evaluate proposals for reducing sedimentation in the lock approaches. For the first, they used Thomas' one-dimensional HEC-6 program, while the latter study relied on TABS-2. As a result of these investigations the Corps constructed design modifications at Lock and Dam No. 1 that significantly reduced the sediment problems in the lock approach channels.[18]

Intensive studies of the four remaining proposed Red River lock and dam sites coordinated numerical models with physical models. This led to a hybrid river engineering approach similar to that pioneered in the Los Angeles/Long Beach Harbor and Columbia River Estuary model projects. Because construction of Lock and

Dam No. 2, prenamed John H. Overton Lock and Dam, was already underway, WES studies of it from 1985 to 1987 shaped efforts at the three later upstream construction sites. All involved coordinated use of four models: three physical models for fixed-bed navigation studies, movable-bed sedimentation studies, and hydraulic structures evaluation; and application of the TABS-2 numerical model for sedimentation analysis. Sediment deposition occurred at Lock and Dam No. 2 after its opening in the fall of 1987, but because the problem had been anticipated based on numerical studies, WES-tested modifications to the original design kept sediment from depositing at the lock miter gates.[19] Incorporation of model study recommendations into the location and design of Locks and Dams Nos. 3, 4, and 5 helped avert similar problems. With the completion of Lock and Dam No. 5 in January 1995, the Red River Waterway opened for commerce after nearly a quarter of a century of work and the expenditure of $1.8 billion.[20]

The Third Dimension: Chesapeake Bay

WES development of a three-dimensional (3-D) numerical model of Chesapeake Bay exemplified the near-complete transition from physical to numerical modeling of estuaries. Through the 1970s and into the 1980s the condition of Chesapeake Bay continued to deteriorate because of its further commercial development and increasing population. Heightened concerns led to the establishment of the Chesapeake Bay Program (CBP) in 1983 to coordinate activities of Federal and state agencies and private individuals toward the goal of Bay restoration. The CBP initiated a concerted effort that soon involved the EPA, the Department of Natural Resources of the State of Maryland, and the Corps of Engineers.

In 1985, the CBP in a major commitment, called for development of a three-dimensional numerical model of Chesapeake Bay capable of assessing its water quality and hydrodynamic forces over time. This reflected the growing confidence that computer modelers could devise a tool of such sophistication. In 1987 the EPA and the Department of the Army signed a Memorandum of Understanding to jointly fund Army development of a 3-D numerical model with WES as the performing agency. The three-and-one-half year, $3.2 million program was of such magnitude that Station Technical Director Whalin directed it personally, using engineers from the Hydraulics and Environmental Laboratories, CERC (which had relocated to WES in 1983), other agencies and institutions, and private contractors and consultants.[21]

After investigating several alternatives, WES researchers decided to adopt a computer program called CH3D (3-D Curvilinear-grid Hydrodynamic Model) as a starting point. Based on a preliminary model developed for WES by Y. Peter Sheng at the University of Florida in 1986, CH3D incorporated a "boundary-fitted grid" capable of simulating the irregular geometries of estuaries, lakes, and coastal waters.[22] Completing the model's development fell largely to Billy Johnson. Working with Joe F. Thompson of the Mississippi State University Department of Aerospace Engineering, Johnson had previously explored the application of boundary-fitted programs to riverine, coastal, and estuarine areas and had introduced the concept to the Corps.[23]

Billy Johnson

When applied to Chesapeake Bay, verification of CH3D proved difficult largely due to the paucity of synoptic data for the extensive bay area and its tributaries. Operation of the Corps' physical Chesapeake Bay model had also suffered from lack of synoptic prototype data. Researchers finally identified three relatively extensive existing data collections that could be used in a verification process. All involved limited time periods: June and July of 1980, April of 1983, and September of 1983. The first provided a good characterization of summer circulation and low inflow conditions of a typical year, the second represented conditions during a large spring runoff, and the third contained a strong wind-mixing event that resulted in

destratification of the bay.[24] Extensive modification of the original computer program resulted in excellent simulation of salinity, temperature, velocity, and tidal phenomena when compared to the three sets of field data. Results from the September 1983 application indicated that the model could even reproduce intense mixing events well.[25] Final verification with a further-improved version of the original CH3D model which makes computations in the vertical on a Cartesian grid replicated year-long events of 1984 through 1986.[26]

By 1991 WES had completed a Chesapeake Bay numerical model, dubbed CH3D-WES, with Johnson, Ronald E. Heath, and Bernard B. Hsieh of the Hydraulics Laboratory and Keu W. Kim and H. Lee Butler of the Coastal Engineering Research Center publishing a comprehensive *User's Guide*.[27]

Chesapeake and Delaware Canal

Use of CH3D-WES for the Chesapeake Bay area extended through the 1990s. In 1989 the Corps' Philadelphia District requested that WES conduct a numerical model investigation of tidal flow and salt transport through the Chesapeake and Delaware Canal (C&D Canal) and their impact on Chesapeake Bay and Delaware Bay. Further studies were to concentrate on the impact on the two bays of deepening the canal from 40 feet to 45 feet. Previous numerical model studies of Chesapeake Bay and Delaware Bay, conducted separately, had not taken the canal into account.[28]

Approximately 16 miles in length, the sea-level Chesapeake and Delaware Canal joins the two large estuarine systems near their northern ends. Its most recent enlargement, started in 1963 and completed in 1975, established an average depth of about 40 feet. Due to its free-flowing form, net flow through the canal changed from easterly to westerly in accordance with tidal amplitudes, densities, wind-driven currents, and other factors. Previous investigations had not completely resolved questions related to the long-term nature of flow and salt transport through the canal, although a study completed by Kuo-Chen Wong in 1991 indicated that those factors played a significant role in the regime of Delaware Bay.[29]

By 1993 Hsieh, David R. Richards, and Johnson had developed a CH3D-WES model that included Delaware Bay, Upper Chesapeake Bay, and the connecting C&D Canal.[30] Model tests conducted by Johnson and Kim first concentrated on seasonal changes in flows through the canal. Results supported earlier contentions that these flows had a substantial influence on salinity both in Upper Chesapeake Bay and in the upper part of Delaware Bay.[31] Further studies, completed in 1997, were broader in scope, calculating numerically the magnitude of net flows through the canal over various time periods (rather than just seasonally), assessing the impact of a 1-foot rise in sea level, and predicting the impact of closing the canal on the hydrodynamics of both Delaware Bay and the Upper Chesapeake Bay.[32]

Calculating possible changes in the salinity of Delaware Bay was of vital importance in deciding whether to deepen the C&D Canal to 45 feet. If deepening permanently increased salinity in Delaware Bay, water supplies in the Philadelphia area could be threatened. Permanent changes in salinity patterns could also adversely affect bay ecosystems, such as oyster beds located in the lower bay. An intensive one-year field data collection effort provided information on a variety of conditions needed to feed into CH3D-WES. These included inflows ranging from the drought of record in 1963 to extremely high flows recorded in 1993.

Ship Simulator

Computerization found another use at WES through the development of a ship simulator for improving harbor and channel design. Carl J. Huval, an irrepressible Cajun who claimed to have not known a word of English until entering the first grade in Breaux Bridge, Louisiana, was instrumental in the development of a WES computerized ship navigation simulator. As a senior in the first accredited engineering class at University of Southwestern Louisiana at Lafayette in 1955, Huval visited WES on a school-sponsored field trip and was duly impressed. After graduation he

Carl J. Huval

accepted an offer from Campbell to join the Hydraulic Analysis Branch despite mutual difficulties in understanding their respective accents. Recognizing the need for further education, in 1958 Huval began a three-year program of study and research at MIT under Ippen and Donald R. Harleman. He then returned to the Station and began a program of on-the-job training in FORTRAN. This combination of advanced studies and computer acumen paved the way for Huval's joining Boyd's Mathematical Hydraulics Group in 1969. Keulegan's paternal guidance, as was often the case, provided Huval further inspiration.[33]

By the mid-1970s Huval and Daggett had become interested in using computer technology to simulate ships passing through channels. The U.S. Maritime Administration was at the time spearheading efforts in ship simulation at its $13 million Computer-Aided Operations Research Facility (CAORF) at Kings Point, New York. Representing the state of the art, CAORF included a ship foredeck and a full-size wheelhouse enclosing a 20- by 14-foot ship's bridge equipped with actual bridge hardware. A 60-foot diameter cylindrical projection screen curved around the wheelhouse, providing pilots with a 240-degree field of view. Five simultaneously operated projectors reproduced color visuals of channels under study, replete with bridges, lighthouses, piers, coastlines, islands, and other ships. For testing and verification purposes, the Maritime Administration brought in experienced deck officers and quartermasters familiar with a prototype area, simulated real-time ship movements through the channel, then recommended adjustments based on their observations.[34]

Although COARF provided valuable information for the Maritime Administration, especially in its mission to prevent ship collisions and other accidents, Huval and Daggett felt that the Corps of Engineers should develop its own ship simulation capability at WES. Their arguments were based on two primary considerations: first, the Maritime Administration's main concern was with ship safety in existing channels, while the Corps needed data to make cost-effective and operationally efficient channel improvements; second, operating costs of COARF were prohibitive. Creating a simple visual database for a typical

Bridge controls, WES ship simulator

COARF study cost about $50,000, while actual simulator operation ran about $1,000 per hour. Individual projects cost up to $100,000 and usually took up to four months to produce a report.[35]

Weighing these factors, in 1975 Huval wrote a formal proposal for WES to develop a ship and towboat simulator for Corps use and, with Simmons' support, made presentations to that effect to OCE. Approval from OCE came despite opposition from some WES administrators who felt that the Coast Guard should take responsibility.[36] After a series of delays, the WES Ship/Tow Simulator became operational in 1983.

Visualization scene, WES ship simulator

The WES simulator replicated a ship's bridge with a wrap-around animated visual display, two radar displays, a ship or tow console, and a precision navigation display. Three mariner-controlled screens provided a 140-degree field of view that could be rotated a full 360 degrees. (Changing the viewing angle thus had the same effect as the pilot in reality turning his head.) One radar display had three variable scales usually set to 1.5 miles, 0.75 miles, and 0.5 miles. The second screen had a 0.25 mile scale and was used to display tugs and thrusters as vectors either pushing or pulling a ship. A navigation display on the third screen showed absolute ship speed, ship speed relative to water, rudder position, engine speed, wind magnitude and direction, elapsed time for the test exercise, and other conditions. The model was capable of calculating ship response to a variety of forces exerted on the vessel, both environmental and mariner-controlled. Environmental forces included currents, bank effects, wind, and waves, while mariner-controlled forces included such things as rudder angle, propeller revolution, and bow and stern thrusters. Whereas most marine simulators could replicate only the three degrees of horizontal motion – surge, sway, and yaw – the WES facility could additionally simulate three degrees of vertical motion – heave, pitch, and roll.[37]

Within 10 years the Station had used the simulator in more than 50 navigation studies, including evaluating proposed improvements to Miami Harbor, Brownsville Ship Channel, San Juan Harbor, Sacramento Deep Water Ship Channel, and Houston Ship Channel. The Brownsville Ship Channel was unusual in that there were only two licensed pilots for the Port of Brownsville, and because of their workloads they were unable to travel to Vicksburg. WES then developed a portable version of the simulator, at a cost of only $30,000, and transported it to Brownsville. Results from the simulator study reduced an original $38.8 million construction estimate by almost $4 million.[38]

WES simulations of conditions and navigation problems in San Juan Harbor provide a case study. San Juan Harbor is the largest port on the island of Puerto Rico and at the time of the WES study in 1992 was the fifth largest container port in the world. Rum, Puerto Rico's main export, is shipped in containers. Noncontainerized products such as petroleum products, automobiles, and steel were also imported via ships, and San Juan received frequent calls from large cruise ships.[39]

By the 1980s ship pilots found two narrow channels within the harbor especially hard to navigate. Winds, waves, currents, and sharp turns presented problems that led to six documented accidents, all groundings, in the two years before the WES study. The Jacksonville District subsequently developed two plans to address existing navigational problems and to allow deeper drafted vessels to use the harbor. Both plans involved channel deepening and realignment. To complicate an already difficult situation, any changes had to avoid undermining El Morro, a historic fort built by the Spanish on bluffs near Old San Juan to protect the harbor from attack.[40]

A WES project team first made a reconnaissance trip to the project site to develop databases for existing and proposed navigation conditions. Among its activities, the team interviewed local experienced pilots to determine navigation conditions in the existing prototype, rode transits with the pilots, and took extensive photos and videos of the harbor area for use in visual scene development. (Although usually uneventful, reconnaissance trips occasionally had hair-raising episodes. Personnel had to become adept at transferring from one moving ship to another on rope Jacob's ladders, a potentially deadly procedure in bad weather. On one harrowing occasion in Delaware Bay, members of a WES team led by Gary C. Lynch encountered 10-foot seas with waves crashing 20 feet up the side of a container ship they were trying to board from a pilot boat. Fortunately, they made it to the leeward side where waves were only three feet high and boarded safely.)

At the Station, Dennis W. Webb, who later succeeded Huval and Daggett as director of ship simulator studies, supervised the generation of databases for the "Maximum Credible Worst Case Scenario," the worst conditions under which the harbor would normally operate, under the assumption that a design acceptable for extreme conditions would be acceptable for less severe conditions. CERC engineers developed a numerical model of harbor waves for simulator use by analyzing 20 years of hindcast wind and wave information, while currents for the existing and proposed conditions were calculated with a TABS-MD model. Two San Juan Harbor pilots then validated the existing conditions database by participating in a series of simulations. Project engineers accordingly modified the databases, when necessary, until simulations reproduced existing prototype conditions as realistically as possible according to the pilots. The actual test series involved six San Juan Harbor pilots over a three-week period at the Station. Possible savings were estimated as high as $23 million.[41]

Continued Physical Modeling

Computerization and numerical modeling, despite advantages in many areas of hydraulic engineering, by no means spelled the doom of physical modeling in the 1990s. While computer-generated programs revolutionized modeling of such hydraulic phenomena as estuarine evolution and riverine sedimentation, physical models continued to serve as more useful tools in other areas. Physical models continue to be irreplaceable, especially where turbulence and/or severe waves, factors poorly understood numerically, are important considerations. In the 1990s, in fact, use of physical models at WES actually increased, with about 30 operative in 1999. Rather than replicating harbors, rivers, and estuaries, as had many earlier physical models, almost all involved hydraulic structures such as bendway weirs, elements of lock and dam complexes, channelized urban flood control systems, or breakwaters. In addition, a new field of physical modeling focused on developing hydraulic structures for environmental mitigation, notably the restoration of salmon migrations in the rivers of the Pacific Northwest.

River Engineering: Bendway Weirs

The Corps created WES primarily to try to control the Mississippi River. After seven decades this has proved to be an unending process, and the mighty waterway continues to resist human regulation. Whereas flood control was the original focus in dealing with the Mississippi, navigation concerns have always been important. With a flood control system largely in place at the end of the century, navigation improvement on the Mississippi remains a major research area.

WES model investigations of a notoriously troublesome reach of the middle Mississippi River led to the development of a revolutionary concept of river regulation – with bendway weirs. Chronic problems at Dogtooth Bend Reach, south of St. Louis and just above the confluence of the Mississippi and Ohio Rivers, led the St. Louis District to sponsor the WES study. Since the 19th century, engineers had tried to improve navigation conditions in the reach by building dikes, the first consisting of willow screens floated by whiskey kegs. By 1984, at the beginning of the WES investigation, the reach had a total of 73 timber or

Bendway weir model

evaluation. However, the complex flows through bends and intricate processes that shape alluvial rivers made numerical analysis extremely difficult. Accordingly, the District called for physical model tests. The Hydraulics Laboratory's River Engineering Branch under Pokrefke then constructed a movable-bed model of about 20 river miles, with David L. Derrick in immediate charge of investigations. Relying on the Station's nearly six decades of river research, the model used crushed coal as movable bed material and crushed limestone sprinkled with cement for bank lines and dikes.[43]

Although tests began in 1984, it was 1988 before Pokrefke developed a new concept of improving navigation on the Mississippi, bendway weirs. Bendway weirs consist of a rock sill (5,000-pound maximum weight stone) located within the navigation channel of a bend, crested low enough to allow normal river traffic to pass over them unimpeded. Model tests indicated that sets of weirs located in the navigation channel of Dogtooth Bend, spaced at certain intervals and long enough to intercept a large percentage of flow, capture, and redirect current directions and velocities through the bend. Of primary importance, the weirs must be angled *upstream* into the flow on the outer bank of a bend. When properly designed and placed, these weirs direct water away from the outer bank and toward the inner part of the bend, improving the navigation channel through the bend and immediate downstream crossing. Among other benefits, bank stability increases because deposition occurs at the toe of the revetment on the outside of the bend, surface water velocities are more uniform, and flow patterns are generally parallel to the banks rather than concentrated on the outer bank of the bend. Bendway weirs also require no maintenance.[44]

stone dikes, 8 underwater sills, and 20 miles of revetments, yet continued to cause navigation problems. Dogtooth Bend was hardly unique. Corps estimates were that 16 bends in the middle Mississippi River and between 65 and 85 bends on the Lower Mississippi River at times experienced inadequate navigation channel widths. Dredging in bendways of the Middle Mississippi River between St. Louis and Cairo alone cost \$4 to \$6 million annually, with an additional \$6 million spent to dredge crossings. The area still averaged 20 bendway groundings per year between 1985 and 1988.[42]

The St. Louis District identified three specific problems at Dogtooth Bend Reach: inadequate navigation channel widths, adverse high-water flow patterns, and an inadequate navigation channel in crossings downstream of bends. The District proposed several plans to improve and stabilize the navigation channel and considered attempting a three-dimensional numerical

Thomas J. Pokrefke

By the late 1990s WES, working in conjunction with the Lower Mississippi Valley Division, had conducted tests in additional bendway models, and the Corps had built over 150 weirs in nineteen bends of the Mississippi River. Results have been outstanding. The first two bends on the Mississippi River with weirs had pre-weir dredging volumes of 1,780,000 cubic yards compared to post-weir dredging of only 56,000 cubic yards. Projected annual savings at each bend was $400,000 for dredging alone. By 1995, at the five oldest weir installations the Corps reduced its dredging operations 80 percent, with savings of approximately $3 million. Further savings due to improved navigation conditions that required less maneuvering of tows were estimated at $720,000 per bend. Towboat accidents declined, as did tow delay times at bends. Sediment and ice management improved. Bendway weirs even proved to be environmentally beneficial by not disturbing least tern nesting areas and by increasing fish size and density in the weir fields.[45]

The Dogtooth Bend project and subsequent bendway weir development at WES received numerous accolades. In 1991 the Chief of Engineers granted a Civil Works Award of Excellence to WES and the St. Louis District.[46] The following year the American Society of Civil Engineers selected WES bendway weir engineering for one of its two Outstanding Civil Engineering Achievement Awards, and WES rewarded Derrick and Pokrefke with the WES Director's Research and Development Achievement Award.[47] An Army Research and Development Achievement Award to Derrick and Pokrefke followed in 1993.[48] In 1994 President Bill Clinton graced the bendway weirs project at Dogtooth Bend with one of two Presidential Awards for Design Excellence given to the Corps that year.[49] Recognition extended beyond professional engineering and political entities: A spokesman for the American Commercial Barge Line said of bendway weirs, "This is the best thing to happen on the river in a hundred years."[50]

River Engineering Continued: Olmsted Locks and Dam

Construction of Olmsted Locks and Dam represented another traditional river engineering endeavor that relied largely on physical modeling. However, despite its six decades of experience in hydraulic structures modeling, WES engineers discovered that the Olmsted project presented new challenges that had to be met with new modeling methods. This project resulted in construction of the largest-scale model ever at WES and controversial design changes that are still under study.

To be located on the Ohio River 16 miles from its confluence with the Mississippi, Olmsted is to replace two older lock and dam complexes (No. 52 and No. 53). In 1988 Congress authorized construction of the new facility at a projected cost in excess of $1 billion, making it one of the largest civil works projects ever assigned to the Corps. As the last dam complex on the Ohio River, its position is vital to commercial interests, providing final passage for all traffic between the Mississippi River the Ohio, Tennessee, and Cumberland River basins. Estimates held that it would be the busiest barge pass in the entire U.S. inland waterway system.[51]

Design of wicket gates for Olmsted Dam was a key concern. The complex was to have twin 1,200-foot by 110-foot navigation locks on the Illinois bank of the Ohio River and a 426-foot-long fixed weir on the Kentucky side. Original plans called for connecting them with a 2,200-foot-wide navigation pass equipped with wicket gates. Wicket gates had been used by the Corps as part of lock and dam systems since 1909. The original dams on the Ohio River, for example, had wooden wickets that were manually raised on hinges to provide navigable depths upstream during periods of low water. During high water periods, about 60 percent of the year, the wickets were simply lowered to the river bottom to allow traffic to pass unimpeded, avoiding the locks. Never, however, had the Corps constructed a dam with wickets such as Olmsted would require. Plans called for 220 remotely operated, hydraulically actuated wicket gates. Each was to

Olmstead Locks and Dam construction site, Ohio River

be 10 feet wide and 26 feet long with a design lift of 21 feet, by far the largest of their type in the world. (By comparison, similar wickets are currently in operation only at deNovaul Dam in France. Spanning an 82-foot-long structure, they are about 10 feet by 8.2 feet in size.)[52]

Design and operation of such large wickets was problematical. The Louisville District first adopted a basic design used at Smithland Dam on the Ohio River and developed a proposed operating procedure. Due to enormous hydraulic pressures that would be exerted against the wickets, especially as they were raised, the proposed procedure called for raising them in groups of five, with five-gate gaps, until 110 gates were raised. The five-gate gaps would then be closed by raising two gates in each gap simultaneously or by raising one gate at a time until all were in place. However, designers feared that conditions during raising and lowering would create uneven hydraulic loading, cause gate vibrations, and threaten the integrity of the structure. Failure of even one wicket could have dire consequences.[53]

WES began studies of Olmsted at about the same time Congress authorized the project, constructing a 1:25-scale model of a 1,250-foot-wide portion of the dam for scour tests. After the Louisville District tasked the Station with wicket tests in 1990, WES engineers modified the model by installing 92 miniature curved wicket gates. One instrumented gate was to measure forces expected on lifting rods and hinges. However, a review of model data in 1992 revealed several shortcomings and led to the construction of another 1:25-scale improved version with flat gates. The earlier model also inadequately represented the structural similarity of prototype wickets and was not intended to simulate elastic relationships. WES engineers, led by Mostafiz R.

Olmstead Locks and Dam model

Olmstead Locks and Dam 1:5-scale wicket gate design model

Chowdhury of the Structures Laboratory and W. Glenn Davis of the Hydraulics Laboratory then designed a 1:5-scale model – the largest-scale model of a hydraulic structure ever built at the Station. It simulated only a 120-foot-wide section of the spillway crest, 12 wicket gates, and approximately 300 feet of the river, both upstream and downstream. An instrumented gate near the center of the model reproduced every intricate detail of the prototype gate, including the materials and entire lifting system. Because the model required an extraordinarily large volume of water to simulate Ohio River flow conditions, WES built it in a huge flume with a recirculating system capable of discharging 200 cubic feet of water per second. Davis supervised experiments from 1993 through 1996.[54]

In the meantime, the Louisville District attempted to test prototype wickets by installing them in a channel constructed on the left bank of the Ohio River near Smithland, Kentucky. A test sequence involved five full-size wickets made of different steels and composite materials with several coatings of different natures. Engineers hoped to evaluate the long-term operational performance of the wickets under a variety of hydraulic conditions and to test the durability, serviceability, and reliability of mechanical components from several manufacturers. Data was to provide guidelines to improve the design of the Olmsted system and its operation. However, the Smithland site could not simulate many of the flow conditions expected at Olmsted, and the Louisville District had to rely primarily on WES tests.[55]

Groundbreaking for the Olmsted complex began with the navigation locks in 1996. As construction of the locks proceeded, the Louisville District dropped plans for remotely operated, hydraulically actuated wicket gates in favor of manually operated ones. Also, rather than constructing wicket gates all the way across the dam pass, five tainter gates, each with 110-foot bays, were to cover about one-third of the distance. This would require less use of the wicket gates and make it easier to maintain and control the pool above the dam. Of primary importance, Louisville District engineers feared that debris such as tree trunks would damage remotely controlled wickets, a circumstance manual operation would prevent. Manual raising of wicket gates simply involves a barge crew starting on one side of the dam raising one wicket at a time, in order, until all are in place.[56]

WES modeling of Olmsted wickets then had to "retool" yet again. Installation of manually operated wickets on the 1:25-scale model led to a series of experiments leading to design recommendations. However, much more precise hydraulic conditions could be replicated by the larger 1:5-scale facility, and installation and testing of the new wicket design was accomplished using that facility.

Urban Flood Control: Los Angeles County Drainage Area

WES investigations of urban flood control processes dated from the late 1930s when the Station ran extensive model tests of flooding in Johnstown. As the century ended, a lengthy and much larger urban flooding model project dealt with another of the nation's most notorious flood-prone areas: Los Angeles County.

In the early 1900s, Los Angeles County initiated a program of channelization of the area's main rivers and tributaries to minimize damage from floods caused by occasional heavy rains. Continued development and modification created a complex flood control system that includes 20 dams, 129 debris basins, and 240 miles of improved channels. Parts of the concreted high-velocity channels serve not only as flood control mechanisms, but as recreational areas and well-recognized backgrounds for scenes in motion pictures including "Grease," "Terminator II," and "Gumball Rally." Despite channelization and other improvements, the Los Angeles area continued to suffer regularly from flooding. Two floods occurred in 1969, two more in 1978, and one in 1980. A single flood in 1983 killed six people.[57]

In the late 1980s a Los Angeles County Drainage Area (LACTA) review, conducted by the Corps' Los Angeles District, concluded that the existing system was incapable of containing the revised, higher flow rates. Several factors, including phenomenal urban growth and extensive storm drain development, had combined to accelerate runoff into the channels and increase flows, threatening the system's capabilities. Additionally, the system appeared to have been designed to handle a 50-year recurrence interval storm, a relatively short period of record. Scott E. Stonestreet, the Los Angeles District's lead project engineer, calculated that a 100-year flood would cover 82 square miles, affecting 500,000 people and 142,000 structures. Potential damages were estimated at $2.3 billion. Failure to further develop the system's capacity invited disaster.[58]

Los Angeles County Drainage Area channel

The Los Angeles District tried to identify improvements necessary to increase flood protection throughout the metropolitan area, but especially in the vicinity of the lower Los Angeles River and one of its tributaries, the Rio Hondo Channel. The sector was the most flood prone in the drainage area as well as the most complex. The seven-mile Rio Hondo Channel between Whittier Narrows Dam and the channel's juncture with the Los Angeles River alone included eight vehicle bridges, four railroad bridges, two pedestrian bridges, bike paths, vehicle access ramps, equestrian ramps, and five bends.

In a first-phase study, the Los Angeles District used a one-dimensional numerical model, WASURO, to calculate flood flows in the Rio Hondo and lower Los Angeles River channels. The district concluded that, in addition to raising parapet wall and levee heights along 21 miles of channels, 1.5 miles of the Los Angeles River immediately downstream from the confluence of the Rio Hondo must be converted from a trapezoidal shape to a rectangular configuration. Of much greater importance, 27 bridges between the Whittier Narrows Dam and the mouth of the Los Angeles River would have to be raised or replaced to safely pass new design flows. Cost estimates ranged up to $530.8 million.[59]

Doubts as to the reliability of its computer model led the Los Angeles District to sponsor physical model studies at WES. One-dimensional models worked well in calculating steady, non-turbulent flows, but their ability to replicate dynamic flows, especially in the trapezoidal channel of the Los Angeles system with its many bridges and other potential obstructions, was questionable. By 1991 WES and the Los Angeles District had entered a research agreement expected to last from 13 to 15 months.[60]

The Station's LACDA studies through the 1990s depended on close cooperation and communication with the Los Angeles District. WES engineers traveled regularly to Los Angeles to meet with local engineers. Even before beginning construction of physical models, lab personnel took photographs and measurements in the drainage area. There they discovered that some specifications in construction plans, especially of bridges, did not match those of the completed structure. Los Angeles District personnel, especially Stonestreet, made visits to WES to monitor progress and provide input. Like various other WES projects, including the Johnstown model studies, tests had to be performed rapidly on an on-call basis as design information and proposed modifications arrived at the Station. Model technicians John Ashley and Van Stewart often worked six-day weeks, 12 hours a day in the models' unheated and un-air conditioned hangar to keep up with the District's needs.[61]

In 1992 the Hydraulics Lab completed three physical models, including the longest indoor flood control model ever built, a 630-foot structure that reproduced most of the channel of the lower Los Angeles River past its juncture with the Rio Hondo Channel, plus most of the Rio Hondo Channel. Two smaller models replicated parts of the lower Los Angeles River in larger scale. All three included miniature bridges, bends, and other phenomena that could affect flows. Channels consisted of plastic-coated plywood and very smooth concrete; the bridges were plastic. Since part of the Rio Hondo side slopes were of grouted stone, WES performed a series of tests in a flume that led to selection of a 0.25-inch wire screen to reproduce the appropriate roughness in the Rio Hondo model. Two later models replicated the confluence of the Rio Hondo Channel and the Los Angeles River, and the upmost mile of the Rio Hondo Channel, just below Whittier Narrows Dam.[62]

Physical model tests, conducted by John E. Hite, Tim Murphy, and Charles H. Tate, produced results that varied widely from those of the numerical model. Findings especially differed in the vicinity of bridge piers, areas characterized by highly three-dimensional near-critical flows not well reproduced in numerical models. Preliminary WES tests, in fact, indicated that 10 vehicle bridges in the study area did not need to be replaced or raised and that certain modifications, notably bridge pier extensions, could further increase the capacity of the bridges to pass flows.[63] Whereas saving one bridge would pay for WES investigations, the Station's model studies eventually saved at least 20.[64]


Rio Hondo model, Los Angeles County Drainage Area

high flows one end of the bridge (or the other) would actually be submerged while the other end remained above an eddy. This was because, rather than spreading equally through the larger channel, the model showed that most flows went either down one side of the flare or the other. If not corrected, this would affect levees as well as the bridge. Further model tests showed that a pair of sills extending almost all the way across the channel bottom would make flows uniform, a solution adopted by the Los Angeles District.[66]

WES recommendations concerning raising or replacing bridges depended largely on a major change in design philosophy championed by Tate, who supervised model testing after 1994. The feasibility study had assumed that for bridges to pass design flood flows effectively, a 2.5-foot clearance between the bridge and the water's surface was necessary. Physical model tests indicated that less clearance was needed. Due to the wide channels associated with the project and the nonuniformity of the flow across channels, in some cases flow could even impact bridges without causing danger. To further increase the capability of bridges to pass flows, WES tested several hundred pier designs to channel and stabilize flows under bridges. In most cases the Los Angeles District used a bulb-nosed pier design developed at WES that extended from 10 to 20 feet upstream. Some bridges required downstream piers, vertical ribs, sills, or other structures. In one case, a bridge needed a 200-foot upstream pier extension.[65]

One Los Angeles River project produced surprising model phenomena that the Los Angeles District had not anticipated at all. Willow Street Bridge crosses the Los Angeles River at its lower end just below the point where the concrete channel ends and makes the transition to a natural bottom. There the channel flares from 300 feet to approximately 500 feet in width. Engineers anticipated that uniform flows in the wider channel would pass safely under the bridge. However, WES model tests demonstrated that at

The WES LACDA studies represent a major triumph in value engineering. By using cost-effective alternatives developed at WES, especially pertaining to raising or rebuilding bridges, and by accepting WES findings that changing the system's existing trapezoidal channel was not necessary, the Los Angeles District reported that approximately $260 million has been trimmed from the project's original estimated cost. Expenditures on WES model studies stand at about $3.6 million.[67]

Environmental Activism: Northwest Salmon

Further Hydraulics Lab involvement in environmental issues grew out of the passage of the 1973 Endangered Species Act, a Federal law requiring preparation of a recovery plan for all species listed as threatened or endangered. Such species are listed when existing conditions or trends are considered to render them in danger of becoming extinct. Recovery plans are intended to direct actions needed to return these species to a condition in which they no longer need governmental protection and can be removed from the threatened or endangered list. Salmon were among the most prominent species affected. As a symbol of the Pacific Northwest, and having great economic, aesthetic, gastronomic, sporting, and even religions importance, they symbolize the culture of the people of the region.

The basins of the Columbia and Snake Rivers, the historic spawning grounds of many sockeye and chinook salmon, were of critical importance. Northwest salmon have very complex life cycles. Migrating from the Pacific Ocean up the Columbia River, then in many cases the Snake, salmon are known to travel as much as 900 miles upriver and climb to altitudes of 6,500 feet to reach spawning grounds. There, in the summer and fall, adults deposit and fertilize eggs in gravel nests called redds. Juvenile salmon use the streams or lakes they were born in as nursery areas for a period of months or even years. Sockeye salmon that spawn in Redfish Lake, Idaho, for example, spend up to three years there before migrating down the Snake and Columbia to the sea. They then range from northern California to the North Pacific, spending two to four years growing and maturing before returning to their natal streams to reproduce.

In their pristine conditions, the Columbia and Snake Rivers provided ideal environments for spawning salmon. However, by the mid-20th century the river basins had been irrevocably altered by man. A myriad of factors then combined to threaten the survival of both sockeye and Chinook salmon. Land use activities such as logging, grazing, and mining ruined spawning areas. Hatchery-produced fish ate large numbers of young salmon, gave them diseases, or competed with them for food and living space. Over harvesting limited population growth. Man's greatest impact on nature, however, was the construction of a series of hydroelectric dams on the Columbia, the Snake, and their tributaries that completely changed the river regimes. Beginning with the completion of the massive Bonneville Dam on the lower Columbia River in 1938, by 1975 the river basins incorporated 14 major dam complexes, 12 built by the Corps of Engineers. Salmon migrating down the Snake-Columbia channels alone had to traverse eight dams; 70 percent of the 471 miles from the mouth of the Columbia River to Lewiston/Clarkston on the Snake River was converted from free-flowing river to reservoirs.

Commercial and recreational fishing were menaces to mature salmon migrating upstream, but losses due to the dams and their operation were more significant. Discharges of water supersaturated with dissolved gases, higher water temperatures caused by flow restrictions, large spillway discharges, and water pollutants posed deadly threats. Migrating fish then had to pass through the dams themselves. This was accomplished by adult salmon swimming upstream through the use of fish ladders built into dam complexes. Fish ladders also provided observation points for biologists to count salmon as they passed through. However, large numbers of salmon "disappeared" between dams, some by falling back over dams after having been counted in the ladder of a previous dam or by dying from injuries received when falling back through turbines, bypass systems, spillways, or navigation locks.

The dams posed much greater dangers to smolts traveling downstream than to adult fish swimming upstream. Before construction of the dams, river flows in the spring migrating season were higher and there was sufficient current to take the smolts unobstructed to the sea. By reducing flows, the dams slowed the rate of downstream travel for smolts by about half, greatly increasing risks for predation and disease. The several routes for passing through the dams also resulted in significant losses. Fish that passed over spillways or through bypass systems had relatively high survival rates. Even those that passed through the turbines appeared to have survival rates of over 80 percent, despite popular perceptions that turbines pureed them. However, these losses took place at *each* dam encountered, eight in the case of Snake River salmon, and were combined with losses by other means. Estimates by the Northwest Fisheries Science Center were that up to 60 percent of all juvenile salmon died as they passed dams and reservoirs.[68] Fewer smolts reaching the sea meant fewer adults to make the upriver trip. Salmon populations spiraled downward.

By 1990 the survival of Snake River sockeye and Chinook salmon was in question. During the 1960s, as many as 4,300 adult sockeye had returned to Redfish Lake to spawn each year. In 1991 no sockeye returned. In 1993 the number rose to eight, but fell to one again in 1994.[69] At Lower Granite Dam, the uppermost on the Snake, an average of 12,700 adult salmon passed the dam each year from 1964 through 1968. This fell to a low of 78 in 1990, then rose to 404 in 1994. Consequently, Snake River sockeye salmon were

placed on the endangered species list in 1991 and Snake River Chinook salmon the following year.[70] In 1995 the National Marine Fisheries Service produced a comprehensive recovery plan for Snake River salmon that tasked the Corps with improving fish passage at its Columbia and Snake River dams.[71]

Salmon and the Corps

Beginning in 1988, the Corps of Engineers had initiated the Columbia River Fish Mitigation project to focus on finding ways to improve its dams' abilities to pass salmon.[72] Shortly thereafter, the Portland District contracted WES to perform model studies to determine what structural or methodical changes could increase fish survival rates. By the mid-1990s this research area, directed by John F. George of the Hydraulics Structures Division, had become one of the largest in the Hydraulics Laboratory. Investigations led to the construction of four large generalized physical models of Columbia and Snake River dam complexes, with two more planned, and a multitude of smaller sectional models that reproduce specific portions of projects or hydraulic structures, such as turbines.

John F George

Some early studies made use of an existing physical model of Bonneville Dam that had been built for navigation investigations. But because each dam in the Columbia/Snake system had distinctive hydraulic characteristics, the Bonneville model could not be used for general studies. WES then began construction of the four large physical dam models, each replicating dam complex structures in addition to substantial upriver and downriver reaches. The Dalles Dam model, completed in 1991, was the first general model built strictly for fish-pass investigations. Construction of models of Lower Granite Dam, John Day Dam, and Ice Harbor Dam followed. Completion of McNary Dam, Lower Monumental Dam, and Little Goose Dam models has since been completed.[73]

Nearly all smolts pass dams in one of four ways: over spillways, through turbines, through bypass systems leading downriver, or through bypass systems leading to collection pools where they are caught and transported downriver in barges or trucks. Each presents certain dangers and each varies at individual dams. The same smolt might also attempt to pass each dam in a different manner. Therefore, general and sectional models of the dams provide invaluable tools to study how smolts pass individual dams in various ways and to enable engineers to develop comprehensive strategies to improve fish passage.

Although smolts that pass over dam spillways have higher survival rates than those that pass through turbines, spillways pose major problems: flows must be maintained at sufficient levels to carry salmon safely over the dam, and hydraulic structures must be designed to either reduce gas supersaturation of spilling water or divert smolts away from supersaturated water. To deal with the first, as early as 1977 the Corps began a program of flow augmentation by releasing water seasonally from upstream storage dams to increase flows on the Snake and Columbia Rivers. Flow augmentations increased through the 1980s and 1990s.[74]

The problem of gas supersaturation led to a lengthy series of WES model studies. The force produced by spill, water falling from heights such as a spillway, creates air bubbles in the water and drives the column of water below the surface of a river at the point of entry. When air bubbles plunge into water, they release or transfer nitrogen into the water, producing nitrogen supersaturation. This increases with the depth of the water column, the amount of time the air is entrained or entrapped, and the amount of time water is held at various depths. Too much nitrogen in water can cause fish to get a sometimes-fatal condition similar to bends in humans. WES experiments led to development of spillway flow deflectors that produce a more horizontal spill flow and limit the plunge depth of water over the spillway, thus reducing gas supersaturaion. By 1998 the WES-designed structures were installed at seven of the eight Columbia/Snake River dams. The Dalles Dam has a shallower stilling basin that

Bonneville Dam model (used for navigation investigations and early salmon studies)

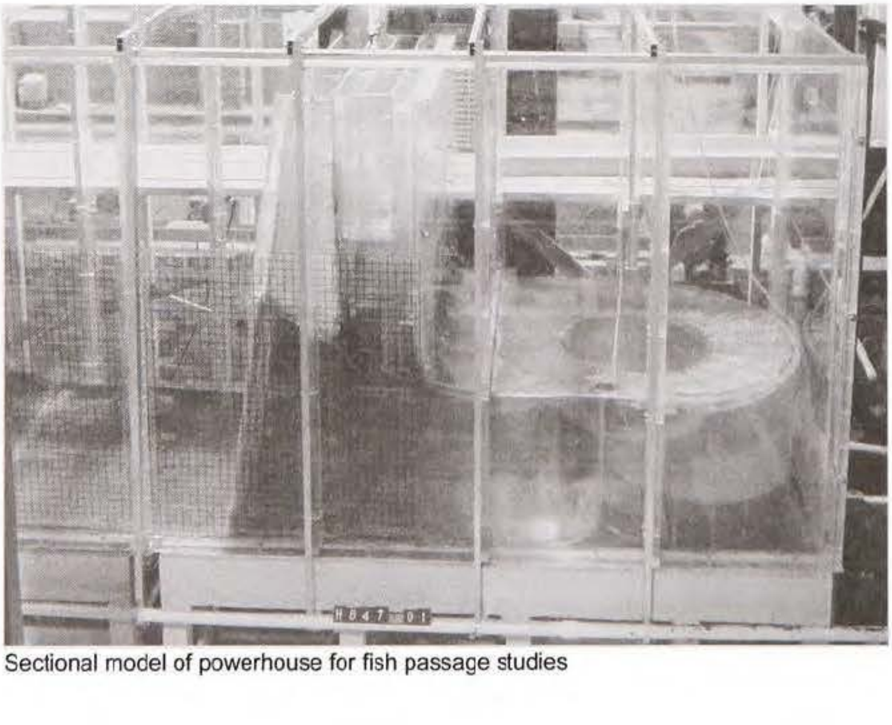
allows higher spill levels with lower gas production, negating the need for flow deflectors.[75]

Like spillways, bypass systems provide safer routes for smolts than turbines. Problems occur when eddies form at or near the locations where bypass channels reenter rivers below dams. Eddies tend to disorient young fish and are the most common location of predators. This consideration led to construction of a large, comprehensive model of The Dalles Dam with lengthy upstream and downstream stretches, the first at WES created exclusively for salmon research. In the prototype, fish screens and traps above the dam and powerhouse successfully diverted most smolts away from the turbines and spillway into a trash and ice sluiceway that emptied below the dam. However, hydraulic conditions below the dam such as gas supersaturation and eddies led to high smolt mortality rates. One purpose of the general model studies is to determine the best design and location of a new diversion channel and where it should reenter the river downstream.[76] In the largest single program expenditure on the Columbia system in 1999, Congress allocated $21.9 million for modifications to the bypass system at Bonneville Dam's second powerhouse and for completion of a bypass outfall. Similar WES studies determined optimal locations for smolts to reenter rivers below the project.[77]

Fish behavior is often frustrating to engineers as well as sportsmen. Despite all attempts to divert salmon from turbines, a substantial number attempt to pass dams through that route. An ongoing WES investigation with sectional models is attempting to determine exactly how and why fish enter turbines, to understand the hydraulic conditions in the turbine environment and how these conditions affect fish, and to develop modifications to turbines or their methods of operation to minimize damage to fish.

Despite massive efforts and expenditures to revive salmon populations, results have been mixed. Counts in 1997 by the Northwest Fisheries

The Dalles Dam model



Sectional model of powerhouse for fish passage studies

Science Center in Seattle still indicated that approximately 5-to-15 percent of smolts died at each dam as they passed turbines.[78] In 1999, however, reports were that a record number of jack salmon (Chinook salmon) returned to the Columbia River. Biologists believe that the return of Chinook to the Snake River in the year 2000 could top two percent of the outmigration – 10 times more than the ratio of 1997 – a figure generally accepted as a goal that would lead to recovery.[79] In any case, WES research in salmon migration and mitigation will continue to be a major area of study.

Watershed Engineering: Demonstration Erosion Control Project

In 1981 the Corps of Engineers estimated that of the 3.5 million stream-miles of channel in the United States, almost 600,000 bank-miles were eroding. Erosion results in serious economic losses of private and public land, disrupted transportation infrastructure, degraded water supplies, and detracts from the aesthetic value of many streams. Sediments wash downstream, clog flood control and navigation channels, and ruin valuable wetlands. Recognizing streambank erosion as a national problem with serious economic and environmental consequences, in the 1980s the Corps began to seek low-cost, environmentally friendly bank protection techniques suitable for landowners, local governments, and other groups with limited financial resources.

The Yazoo River Basin in northwest Mississippi provided a case study in the creation and evolution of an eroding stream system. Typical of many drainage basins around the country, the erosional history of the Yazoo Basin was described by one engineer as "a tragedy of neglect and ill-planned land use and channelization." Rapid agricultural development in the 19th century gave no consideration to proper soil conservation practices. The transformation of virgin forest with very little cultivation to aggressive cultivation of the Yazoo Basin's hills led to massive erosion of soil into the floodplain and channels of the valleys. Sand and debris restricted drainage in the valleys and buried croplands. By the late 19th century, a number of local organizations formed for the purpose of channelizing streams in the Yazoo Basin, but a lack of coordination, coupled with poor engineering practices, tended to worsen rather than alleviate the situation.[80]

Finally, in the mid-1950s the Federal government became actively involved. The U.S. Department of Agriculture's Soil Conservation Service began to coordinate activities on a total watershed basis, without restrictions by county boundaries. Measures included introducing conservation cropping practices, revegetation, terracing, channel clearing and snagging, channel excavation, and cutoffs. Results were mixed. In some cases streambeds continued to incise as much as 25 feet below original bank levels, causing widespread bank instability and failure. Federal involvement increased greatly after a 1984 act of Congress directed the Corps of Engineers and the Soil Conservation Service to devise a comprehensive erosion, sediment, and flood control program for six watersheds in north central Mississippi. By 1989 an additional nine watersheds had been added to the project, and one more in 1996. Titled the Demonstration Erosion Control (DEC) Project, the effort eventually involved WES, the Vicksburg District, the Department of Agriculture, the U.S. Geological Survey, Colorado State University, and the University of Mississippi.[81] Lessons learned from the DEC Project serve as a model for restoration of similar drainage basins around the country.

DEC activities, supervised by Nolan K. Raphelt, ran a technological gamut from the most sophisticated to the simplest forms of fighting erosion. Three examples are:

- the use of state-of-the-art numerical modeling to compute bank stability and sediment transport,
- construction of bendway weirs in small waterways, and
- planting willow posts on streambanks.

By 1994 the Corps had devised numerical methods for determining required bank stabilization methods, primarily through a computer program called "SAM -- Hydraulic Design Package for Flood Control Channels." SAM computes stable channel dimensions, width, slope, and sediment yield. A program called HEC-2 computes hydraulic characteristics. BURBANK used input from the HEC-2 analysis to develop bank stability along the reach.[82] Bendway weirs, first used to improve channelization and navigation on the Mississippi River, proved effective on much smaller streams in the Yazoo Basin, such as Harland Creek. There, a combination of bendway weirs, willow posts (large native willow cuttings planted in eroding banks), and other remedial works were included in a comprehensive effort at bank stabilization. At a total cost of $322,845, a contractor placed over 9,000 willow posts and installed 54 bendway weirs in 14 eroding bends. Although

some of the weirs were originally located or angled incorrectly and over half the willow posts died in the first year, results after four years were outstanding.[83] Lessons learned from Harland Creek and other sites led to improved weir design parameters and better methods of willow post planting on more recent projects. Drawing on its experiences with the DEC project, the Station completed a lengthy *WES Stream Investigation and Streambank Stabilization Handbook* for the Environmental Protection Agency in 1997.[84] A draft *Demonstration Erosion Control Design Manual,* written under contract by Chester C. Watson of Colorado State University in 1998, also serves the nation's needs in watershed engineering.[85]

Military Hydrology

Military research received a welcome boost in the 1990s when the Hydraulics Lab assumed control of a burgeoning hydrology program. Military hydrology, the area of study that deals with the characteristics of surface and subsurface water features that may affect the planning and conduct of military operations, had a lengthy pedigree stretching back to the Roman Empire. Studies at WES began in the late 1970s. Army strategists at that time expressed concern over the paucity of effort expended by the military on hydrologic capabilities since the 1950s, despite a pressing need for more rapidly delivered hydrologic data over larger areas. The Army, in fact, lacked much of the hydrologic technology in common use by the civil engineering community. In response, OCE in 1977 initiated a "Hydrology Support for Military Operations" work unit in the Environmental Systems Division of the WES Mobility and Environmental Systems Laboratory. Directly supervised and aggressively supported by L.E. "Ed" Link, Jr., the group became the only military research-oriented unit of the new WES Environmental Systems Laboratory (EL) in 1978.[86] (The Mobility and Environmental Systems Laboratory, facing a declining mobility but growing environmental workload, was disbanded. Mobility studies returned to the Geotechnical Laboratory, where they had begun in the early 1950s. Environmental studies became the focus of a new WES laboratory.)

Through the 1980s, a number of military hydrology studies by the WES EL group concentrated on forecasting floods resulting from dam breaches or reservoir drawdowns. (WES dam-breach studies date from World War II when the Station attempted to assess the impact of dam breaches on the upper Rhine River. A primary product of these studies was the creation of a numerical Han River (Korea) Control System.[87] Encompassing about one-fourth of the land area of the Republic of Korea, the Han River basin and its network of dams provided an object lesson for the potential of military hydrologic engineering during the Korean Conflict. In 1951, for instance, the North Koreans opened floodgates of Hwachon Dam, creating a floodwave that severed two Allied floating bridges. The next year United Nations aerial forces breached two Han River dams in North Korea. Resulting floods destroyed or damaged miles of railways, highways, bridges, and buildings, and silted in miles of irrigation canals. Main supply lines to the south were cut for two weeks, and the all-important Korean rice crop suffered irreparable damage.[88]

By the 1980s Army strategists were particularly concerned that North Korea could, in time of war, capture several Han River dams south of the DMZ. If captured before much of their reservoirs could be emptied, these dams could be used to release water and disrupt operations downstream. United States and South Korean forces then needed the capability to predict how long it would take to draw down specific reservoirs, information that could determine if such dams should be heavily defended until their reservoirs were sufficiently emptied.[89]

By 1986 the WES EL group, including Mark R. Jourdan, had produced a one-dimensional computer code to evaluate Han River Reservoir drawdown operations. Originally called the Reservoir Analysis Model for Battlefield Operations (RAMBO), this first-generation application had several shortcomings. Further efforts led to development of a more comprehensive and widely used TACDAM numerical model.[90]

While military hydrology emerged as a highly-visible part of the Environmental Lab's activities, the Hydraulics Lab quietly developed its own capability. Although hydrology was not a recognized part of the HL mission, Herrmann, after becoming HL Director, and McAnally decided that surface and groundwater hydrology could be growth areas for the lab. McAnally's Estuaries Division then gradually hired engineers with knowledge in those fields. For example, Tony Thomas recruited and McAnally hired William D. Martin, who had both sedimentation and watershed hydrology experience. Although most work was civil, a small amount of funding from the Army provided for military studies in rapid detection of drinking water.[91] Martin would excel both technically and administratively, and in 2002 would be selected as Deputy Director/Chief of Staff of the Coastal and Hydraulics Laboratory.


William D. Martin

A major contributor to HL hydrology research was discovered quite by accident. Norm Jones, an engineering graduate student at the University of Texas, developed a MacIntosh computer program to graphically display and analyze geologic data. Called NGRID, its user interface appealed to WES HL engineers R. Charlie Berger and David L. Richards, who were also engaged in graduate studies at Austin. Jones converted NGRID from its original MacIntosh format to IBM to suit WES needs. It now stands at the progenitor of several hydraulics- and hydrology-related numerical models for the TABS system. After earning a Ph.D. at the University of Texas, Jones accepted a faculty position at Brigham Young University, where he continues to work with WES engineers in the development of hydrology computer programs.[92]

By 1992 the Environmental Lab's efforts in military hydrology were disjointed. In a surprising decision, WES Technical Director Whalin announced to his lab chiefs at a retreat that most military hydrology research would be removed from EL and assigned to other WES labs. Four EL hydrologists, including Jourdan, transferred to the Hydraulics Lab to join Martin's group. This cadre formed a Modeling Systems Branch, still within the Estuaries Division.[93]

By the mid-1990s, efforts involved computer modeling in three distinct hydrologic areas: watershed modeling, groundwater modeling, and subsurface modeling. All involved development of two-dimensional programs derived primarily from the earlier NGRID program or from an improved version named FASTABS. To standardize nomenclature in its expanding numerical program, HL labeled the three WES numerical model graphical user environments the Watershed Modeling System (WMS), Groundwater Modeling System (GMS), and Surfacewater Modeling System (SMS). During Herrmann's tenure, Jeffrey P. Holland moved from his position as Chief of the Reservoir Water Quality Branch to become Special Assistant to the HL Director. In that role he tirelessly worked to promote the Groundwater Modeling System, including the FASTABS user environment. Federal agencies and universities subsequently became partners in the development of GMS and associated groundwater models, and the Department of Defense designated GMS as its official groundwater modeling system. By the late 1990s groundwater modeling studies performed in partnership with the WES Geotechnical Lab were a significant and growing part of the Hydraulics Lab's workload.[94] Holland's combination of engineering and modeling expertise and his direction of the GMS effort marked him as one of Army and DoD's computational technology leaders. In 2001, he was selected as Director of the Information Technology Laboratory.


Jeffrey P. Holland

Although originally funded primarily by the Environmental Protection Agency, by the late 1990s WES work in watershed modeling was entirely military. Groundwater modeling work is also predominantly for the Army, largely involving detection of subsurface groundwater contamination at military facilities and development of

plans of remediation. The Army saves millions of dollars annually by determining the proper number and placement of drainage wells alone. Nearly all surfacewater research is non-military.

Hydrology in Practice: The Sava River Challenge

In December 1995, more than 20,000 American troops prepared to enter Bosnia from Croatia as part of a United Nations peacekeeping force. Because bridges crossing the Sava River into Bosnia had either been destroyed in the recent civil war or could not handle the heavy loads of military traffic, Army planners prepared to build a floating "ribbon" bridge across the Sava at Zupanja, Croatia. Capable of handling M-1 Abrams tanks, the bridge design originated in Germany during World War II and was captured by the Russians at war's end. In turn, Soviet-built bridges captured by Israelis in the 1973 Arab-Israeli War provided the basis for an American version. Spanning the Sava was to be its first "real mission" use and the largest river crossing by military forces in Europe since 1945.[95]

In an exercise in poor planning, engineers built an access road to the planned bridge site and a construction camp well within the Sava floodplain. The camp was actually inside the Sava levees. Rain and unseasonably warm temperatures that melted snow caused the Sava to rise above flood stage. Normally about 14 feet deep at Zupanja at that time of year, the river quickly became a 21-foot-deep torrent. By Christmas Day, the access road was under water and the construction camp abandoned. American troops sat idly, some as long as two weeks, while Army commanders debated the next course of action. No one knew whether the river would continue to rise or whether the projected bridge could withstand flood flows.[96]

At approximately 3:00 a.m. on 26 December 1995, WES Commander Colonel Bruce K. Howard received a call from the Army captain in Croatia charged with building the Sava bridge. Requesting assistance, the latter was especially concerned as to how long the bridge and roads to it should be. Howard immediately roused Martin and other members of the military hydrology group, and within hours a WES Sava River Hydrologic Team was in place. Working for days almost around the clock, the group collected information from any available source. Limited flood stage data from the Croatian Flood Ministry, procured by a British operative in Zagreb and FAXed to WES, proved invaluable for short-term projections. Relying on "seat-of-the-pants engineering," WES started making river predictions within 72 hours. Conclusions were that the river would not continue to rise in the immediate future. This enabled onsite engineers to overhaul construction specs and methods. In a masterpiece of improvisation, Chinook helicopters lowered prefabricated

Construction of Sava River bridge

Sava River bridge in use

bridge sections into the swollen Sava during a heavy snowfall. Crews pieced them together and pushed them into place with jet propelled boats. Traffic began passing less than 24 hours after bridge construction began.

With the immediate crisis resolved, the WES group began developing a comprehensive Sava Basin model for continuing use. Spring flooding, in fact, would be much more severe than the December anomaly, and the pontoon bridge would remain in use indefinitely. Martin, Jourdan, Thomas L. Engdahl, Jeffrey D. Jorgeson, and others on a WES team that at one time numbered almost 20, expanded sources to include digital terrain data from the Topographic Engineering Center (TEC), information from Internet sources, satellite photos, and weather and news reports on CNN. The WES Geotechnical Lab furnished data on soil characteristics, while the Cold Regions Research Engineering Laboratory (CRREL) shared information purchased from a variety of sources. In a stroke of good fortune and bravery, a Yugoslav source retrieved two forgotten volumes of United Nations data from a bombed-out building in Sarajevo and had them forwarded to WES. Two Hydraulics Lab engineers also joined six from other WES labs and CRREL "on the ground" in Bosnia for first-hand observations. (WES geotechnical engineers, relying on years of trafficability and mobility research, provided detailed analyses of mobility corridors based on soil and vehicle performance characteristics.)

By March 1996 the HL "Bosnia Boys," down to working only 12 hours a day, provided river predictions up to 10 days into the future. Creation of an Internet Sava River web site enabled WES to furnish real-time information to troops in the field. Never in history had commanders had such rapid and accurate information on a river. Still, the Station fielded questions by telephone and Internet from the Balkans on a daily basis, as the Army became increasingly hesitant to act without WES input. One soldier, for instance, called WES and asked for the river stage while standing by the Sava bridge gage. Apparently he only wanted to know if he was reading it correctly.[97]

WES contributions to the Bosnian operation brought international recognition. NATO leaders noted that no European member had the capability to perform tactical hydrologic calculations, even for European rivers, as quickly or accurately as the Station despite its remote location. For his actions in leading the Sava project, in June 1996 the Army granted Martin a Meritorious Medal for Civilian Service. Martin further lauded his group's efforts,

stating that "No other engineers in the world could have done this as accurately or as fast." The Army, learning from its Bosnian experience, currently funds WES hydrology studies aimed at predicting river behavior around the world for tactical purposes. Much of this research relies on data obtained from satellites and other remote sensing devices.[98]

Organizational Change and The Merger

The Hydraulics Laboratory experienced several administrative reorganizations and personnel changes between 1983 and 1996, though none altered its fundamental structure. The departure of Whalin's Wave Dynamics Division for CERC in 1983 left four lab divisions: Waterways under Glover, Estuaries under McAnally, Hydraulic Structures under Grace, and Hydraulic Analysis under Boyd. (See Appendix A: Organization Charts.) After serving for 11 years as Assistant Chief, in 1984 Herrmann succeeded Henry Simmons as HL Chief, a post he held until 1995. By 1988 Boyd had succeeded Glover as head of the Waterways Division, which then absorbed Boyd's Hydraulic Analysis Division. Pickering replaced Grace as Hydraulic Structures Chief.

At Herrmann's retirement, Sager became the Hydraulics Laboratory's Acting Director, with Robert F. Athow as Acting Assistant Director. McAnally's Estuaries Division then merged with part of the Waterways Division. Phil G. Combs replaced Pickering as head of the Hydraulic Structures Division. A new Navigation Division appeared under Daggett, as did a Hydro-Sciences Division under W.D. Martin.


Phil G. Combs

These administrative cycles paled in comparison with "the merger" of 1996. Despite their independent traditions of success, both HL and CERC encountered severe financial difficulties in the mid-1990s. Federal budget cuts, declining workloads, and high overhead resulted in the two organizations downsizing to become the smallest of the six WES laboratories. The combined workloads of HL and CERC, for example, fell from a high of $80 million annually to less than $55 million. Pressure from Congress for the Corps to engage in more contracting lent further instability.[99]

In a monumental decision, Station Director Whalin quietly opted to merge the two entities. Although rumors were rife, a relatively unsuspecting CERC Chief James R. Houston reported to Whalin's office on a Friday in 1996 for a private meeting. There Houston learned officially that the laboratories would unite and that he would be head of a new Coastal and Hydraulics Laboratory (CHL).[100] Personnel of both labs met the announcement with a degree of shock. HL employees were particularly disturbed at the prospect of the oldest WES laboratory losing its identity.

Houston, upon assuming direction of the new CHL in October 1996, felt that his most pressing task was to reduce laboratory overhead to make the organization fiscally solid. Dire predictions became a reality when by February 1997 laboratory income was insufficient to cover salaries. Houston, with Whalin's support, initiated a major administrative overhaul and very difficult program of staff reduction. Through a series of retirements, buy-outs, and transfers, the laboratory eventually lost almost 70 positions ranging from an assistant laboratory director to division chiefs to secretaries.[101] From seven divisions at the time of the merger, by the end of 1997 Houston had crafted four: Estuaries and Hydrosciences under McAnally, River Structures under Combs, Navigation and Harbors under Claude E. Chatham, Jr., and Coastal Sediments and Engineering under Thomas W. Richardson.

By 1999 CHL was recovering from the doldrums of a few years earlier. As the largest coastal and hydraulics engineering laboratory in the world, its reimbursable workload again reached $60 million. Part of this success was due to increased synergies and interdisciplinary projects with other WES laboratories. Houston also aggressively marketed the laboratory's capabilities to foreign clients in areas such as breakwater

engineering, a major CERC research area before the merger. In spite of limited budgets, some new hires of young engineers insured a continuum of new ideas into the Laboratory.[102]

U.S. Army Engineer Research and Development Center

Restructuring and budget cuts at WES reflected national trends. Several Department of Defense initiatives, beginning in 1989, began to streamline its research and development organizations. This resulted in closing several facilities, reorganizing laboratories, and reducing manpower. Despite substantial savings, Congressional acts of 1996 and 1998 required the Secretary of Defense to achieve even greater savings by eliminating overlap and identifying further ways to increase efficiency. DoD guidelines also required its laboratories to achieve a 25 percent reduction in costs by 2005.[103]

When DoD began belt-tightening measures, the Corps of Engineers maintained independent R&D laboratories at four sites:

- WES, with separate Coastal and Hydraulics, Geotechnical, Structures, Information Technology, and Environmental laboratories,
- the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire,
- the Construction Engineering Research Laboratories (CERL) in Champaign, Illinois, and
- the Topographic Engineering Center (TEC) in Alexandria, Virginia.

In the fall of 1998, however, the Corps initiated a "re-engineering" plan to consolidate operations of the separate laboratories under a single organization structure. A new organization, the U.S. Army Engineer Research and Development Center (ERDC), assumed overall control. Headquartered at the WES reservation, ERDC centralized the business, administrative, and support personnel and functions for all Corps laboratories. The individual laboratories at the WES reservation, along with the three laboratories at other locations, began reporting to the ERDC Director, who in turn reported to the Deputy Commanding General of the Corps of Engineers. This marked a shift from the previous reporting practice in which the three remote laboratories had reported to the Director of R&D at the Corps' headquarters and the WES laboratories had reported to the WES Director, who in turn reported directly to the Director of R&D.

WES, therefore, no longer functioned as a separate administrative unit; instead it became the location for the ERDC headquarters. CHL Director Dr. James R. Houston became the first ERDC Director and WES Commander Colonel Robin Cababa became first ERDC Commander. In 2001, Walter F. Morrison, Jr., was selected as the first Deputy Director to assist Houston in the overall leadership in the organization. With Houston's departure from CHL in June 2000, Thomas W. Richardson, the Deputy Director of CHL assumed leadership of that laboratory and was selected as permanent CHL Director in March 2002. Richardson had served for 3 years as an officer in the U.S. Army Corps of Engineers prior to beginning his civilian employment in 1974 as a Research Hydraulic Engineer in the Hydraulics Laboratory. In 1983 he joined the CERC becoming Chief of the Engineering Development Division specializing in prototype investigations, measurement system development, and field evaluation studies.


Thomas W. Richardson

With the restructuring of the Corps' R&D mission came a redefining of leadership roles that continues today. The ERDC Director, a civilian position, has overall responsibility for ERDC, similar to the role of the commanding officer for a Corps of Engineers division command. In the absence of the ERDC Director, the ERDC Deputy Director, another civilian post, exercises overall responsibility. The ERDC Commander, a military officer, also designated as Executive Director, has a two-fold role. As Commander of the ERDC "installations," the military officer oversees the ERDC Command

Staff Division, which is comprised of Resource Management, Public Works, Security, Public Affairs, Safety, Logistics, EEO, and Audit. As Executive Director, the ERDC Commander assists the Director and Deputy Director in planning and executing the R&D program conducted by the seven ERDC laboratories with particular emphasis on identifying and understanding warfighter requirements and providing liaison to installations and the Engineer Regiment.

Future Direction: ESTEX Hyperflume

Ironically, in an age dominated by computerization and numerical modeling, a huge project intended to keep CHL in the forefront of hydraulic engineering involved a return to one of the field's earliest tools: the flume. As early as 1891, Hubert Engels, hydraulics pioneer at the *Technische Hochschule* in Dresden, Germany, was impressed by a glass-sided flume at the University of Michigan designed to illustrate the flow of water over a weir. By the early 20th century flumes had become invaluable tools at both European and American research facilities. From the Station's inception, WES engineers had used flumes in experiments involving movement of bed-load materials, and during the 1940s and 1950s Keulegan relied almost exclusively on flume tests in his seminal work on saltwater intrusion.

By the 1980s, however, doubts arose as to the accuracy of a number of hydraulic calculations derived from flume research, especially those influenced by "sidewall" effects. Such effects are the product of the narrowness of flumes in relation to their depths. Keulegan himself ultimately concluded that all salinity flume work was flawed and that flumes with at least an 8:1 width-to-depth ratio would be necessary for future work. By the late 1980s, other WES engineers openly questioned results of flume tests. This in 1989 led HL leaders, including McAnally, to propose construction of a large 10:1 ratio flume at a cost of about $1 million. McAnally's efforts in numerical modeling had not excluded support of physical studies. Noting that "there is no substitute for watching water," he had by the 1990s concluded that computer-oriented engineers often literally lost sight of the physics involved in hydraulics, and that field experience was an invaluable complement to numerical studies. Further, because numerical modeling by the 1990s could be done by researchers at almost any institution with sufficient computer capacity, physical modeling at WES was likely to gain renewed vigor in defining the Station's unique research capabilities.

On receiving the HL flume proposal, Whalin insisted that it be expanded to provide for a $20 to $30 million facility. Seeking a more realistic compromise, McAnally sought input from the academic community as to its needs and recommendations in flume research, making use of a $25,000 grant from the National Science Foundation. Most importantly, in 1994 he hosted a conference of hydraulics specialists specifically to discuss uses and possible design of a "superflume." Conferees, including Ray Krone, concluded that even a 10:1 ratio flume was inadequate. This led to development of a WES flume design, revised several times, with a projected cost of $4 million. For several years, attempts to acquire funding were discouraging. Then, just as McAnally was about to abandon hope, in 1998 the Corps approved the project and provided $60,000 for design specifications.

Specifications eventually called for a flume 520 feet long and 420 feet wide constructed within a large existing WES building. The facility itself was to consist of three integrated components:

- a main basin 420 feet long, 60 feet wide, and 4 feet deep,
- an adjoining flume 480 feet long, 10 feet wide, and 4 feet deep, and
- a deep water basin 58 feet long, 60 feet wide, and 10 feet deep.

These dimensions would dwarf all existing flume-related facilities. (In contrast, the largest flume in use at the time, located at the Delft Hydraulics Laboratory, Netherlands, was 100 meters long and 1 meter wide.) The main basin was to include temporary partition walls for subdividing it into basins of smaller widths. Tides as well as unidirectional flows could be generated in both the main basin and the flume, which could be operated

independently. While the basin was designed mainly for three-dimensional model studies, the flume was to be mainly for two-dimensional model studies and fundamental research.

Dubbed the "ESTEX Hyperflume," the WES facility was intended to provide new and unparalleled opportunities to ERDC researchers as well as to students and faculties of universities. Specific research areas include but are not constricted to:

- estuarine stratified flows,
- outfall studies,
- physical scale models,
- erosion of sediment mixtures,
- interface stability,
- flocculation under turbulent flow,
- optical backscatter sensor calibration,
- fluid mud studies,
- sediment deposition under stratified conditions,
- wetland studies,
- deposition of sediment, and
- dredging studies.

Construction of the facility began in October 2000 after several delays. The majority of construction was completed by fall 2001, with operation and full instrumentation commencing the following year.

The WES Mission Continued

The Coastal and Hydraulics Laboratory enters the third millennium both proud of its vaunted past and confident of its future. Despite an impressive legacy of change, certain constants formed the broad foundation upon which the success of hydraulics engineering at WES is based. These include:

- the Station's ability to effectively shift priorities and administrative structures as circumstances dictated,
- the enthusiasm and ability of its founders and leaders,
- its unmatched skilled technicians,
- its unique ability to interact with the public, private, and academic sectors, and
- the necessary support from higher authorities in the Corps of Engineers and other Department of Defense agencies.

As described in Chapter 1, the WES role has historically been essentially reactive. Whenever the Corps of Engineers encountered changing political, economic, scientific, and engineering pressures, WES responded accordingly. Even the establishment of WES was in reaction to the natural disaster of the Mississippi River Flood of 1927, to increased political pressures on the Corps to control flooding, and to new theories of hydraulic modeling pioneered in Europe. The Station, functioning for 75 years as the location of the Corps' primary hydraulics engineering research facility, reflected the Corps' changing priorities on a continuing basis. Administrative overhauls, the appearance and disappearance of whole research units, the decline of activities in some research areas while whole new fields of endeavor gained prominence, have been commonplace. Changes in the administrative structure of the Hydraulics Division and Hydraulics Laboratory clearly illustrate these transitions. In several cases engineering areas began activities under the umbrella of the hydraulics administrative structure before splitting off into separate organizations. For example, although the original WES mission was strictly in hydraulics engineering, when soil mechanics became a distinct engineering discipline in the 1930s, the Station made pioneering efforts in that field which soon led to the establishment of a Soils Division. During the Cold War, nuclear weapons effects became an important research area in the Hydraulics Division before becoming a separate entity. In the 1970s, when environmental quality became a major issue to most Americans, the Hydraulics Laboratory spawned, then spun off a major environmental research organization. Thus the WES tradition, established almost at the Station's inception and encompassing the lengthy history of the Hydraulics Division and its organizational successors, was one of flexibility and of adapting to meet ever-changing demands.

Organizational structures cannot be effective without capable leaders. The Station, both in its overall command structure and in its hydraulics engineering entities, has benefitted from

extraordinarily talented and dedicated personnel. Perhaps Vogel in particular deserves credit for establishing a *spirit* at WES emblematic of the Corps' motto: "Essayons," or "Let Us Try." The arrival of the 29-year-old second lieutenant in Vicksburg via "a long dusty road with a cemetery at the end of it" in late 1929 was hardly seen as promising at the time. Yet despite political and even professional opposition, he carved a facility, literally out of a wilderness, that eventually became a world leader in many fields. A key to this success was unquestionably the *iconoclasm* of Vogel and his successors. The spirit of being "eager to prove Newton wrong" and the readiness to challenge the status quo, became the WES tradition. This tradition continued through generations of engineers, scientists, and technicians eager to take on new fields and new tools, as exemplified by unprecedented accomplishments in physical modeling followed by the early adoption of the computer revolution. From Vogel's innovations in hydraulic modeling, Tiffany's perfectionism, Simmon's revolutionary estuarine research, Keulegan's mathematical rigor, and Boyd's advocacy of numerical models, leaders came along at the crucial times, sometimes revolted against the scientific and bureaucratic establishment, and created new paths for their successors. New leaders continued (and continue) to advocate new revolutions.

Perhaps least appreciated among contributors to hydraulics engineering at WES, especially in relation to physical modeling, was the cadre of skilled technicians who actually constructed and often operated the Station's hydraulic models and other hydraulics facilities. This legacy dates from the Station's creation when Vogel employed and trained workers from the Vicksburg area in model construction, then hired college graduates, glad to have any kind of employment during the Great Depression, as "laborers." Early on, these technicians set precedents for excellence not matched by any other research institution, either public or private, a tradition continued still. Many agree that whereas the "brainpower" found at WES could sometimes be found elsewhere, in academic or other research institutions, the Station's modeling capacity could not be replicated, primarily because of its skilled craftsmen. The idea of constructing huge, revolutionary physical models such as the Lower Mississippi River Flood Control Model in the 1930s or the enormous Mississippi Basin Model in the 1940s and 1950s was unthinkable to other institutions or agencies who did not have the skilled manpower available to WES. Far from Vicksburg, even construction of the Chesapeake Bay Model in Maryland and the San Francisco Bay Model in Sausalito relied heavily on the skill and experience of WES labor. To these unsung heroes goes much of the credit for the Station's modeling legacy.[104]

Perhaps most unusual about WES is its complex relationship with the public, private, and academic worlds. Unlike many other Federal institutions, WES never functioned in isolation. From the beginning, the Station forged contacts in the corporate sector and in academe that helped shape its direction and mission. Consultants to WES historically included the finest minds and most respected academicians and practicing engineers in the world. Consulting boards and committees, such as the Committee on Tidal Hydraulics, gave WES insight into the most current engineering trends and representation in shaping policies to implement engineering practice. Hosting conferences on vital issues and developments in hydraulics engineering provided further contacts with leaders in the field. WES engineers historically were leaders in professional organizations such as the ASCE and contributed to numerous scholarly publications, benefitting from interaction with other specialists in their fields. Hardly any professional conference in hydraulics engineering anywhere in the world was without some form of WES participation. Further, the WES program of continuing education provided opportunities for dozens of engineers to keep up with the latest developments in the academic world and to forge valuable contacts therein.

Finally, WES could depend on the Corps of Engineers, the Army, the Department of Defense, and Congress for commitments to engineering excellence. Few private institutions could compete with the Station in terms of financial support for engineering projects, manpower, and research. Construction of the world's largest, most complex,

and most accurate physical models could not have been achieved without massive public assistance. Hiring and maintaining talented staffs of professional engineers, scientists, and skilled technicians was made possible through governmental support. Establishment of a DoD supercomputer center at WES insured that the Station's engineers would have an electronic computing capacity second to none, while construction of the ESTEX Hyperflume placed WES far ahead of other research institutions. Yet, despite its reliance on governmental support in these areas, few public institutions could compete with WES in its support from and interaction with the private sector and scholarly world.

In summation, in its first 10 years of existence, the U.S. Army Engineer Waterways Experiment Station rose from obscurity to earn a position at the forefront of hydraulics engineering. After another six decades, the Engineer Research and Development Center's Coastal and Hydraulics Laboratory, WES, continues that tradition. Because the Corps is firmly entrenched as the primary national agency dealing with many aspects of hydraulics engineering, flood control being a primary example, it is safe to assume that CHL will continue to serve the Corps' and the nation's engineering needs far into the future. New engineering and political challenges will continue to arise, and the Corps, if its past is to be a guide, will continue to adjust its structure and focus to deal with those challenges. CHL rests on a solid foundation, a foundation built over decades of service. May that foundation be only a beginning.

Notes

1. William H. McAnally, interview by author, Vicksburg, 25 June 1999.

2. See William A. Thomas and William H. McAnally, "User's Manual for the Generalized Computer Program System: Open-Channel Flow and Sedimentation, TABS-2," WES *Instruction Report HL-85-1* (Vicksburg: WES, 1985).

3. William A. Thomas and Ronald E. Heath, "Application of TABS-2 to Greenville Reach, Mississippi River," in Charles M. Elliot, ed., *River Meandering: Proceedings of the Conference Rivers '83 Sponsored by the Port, Coastal and Ocean Division of the American Society of Civil Engineers, October 24-26, 1983* (New York: American Society of Civil Engineers, 1983), 908-919; and Thomas and McAnally, "User's Manual."

4. The primary reason for the increase in sediment load was apparently the growing capture of the Mississippi's flow by the Atchafalaya.

5. See William H. McAnally, Samuel B. Heltzel, and Barbara P. Donnell, "The Atchafalaya River Delta. Report 1: A Plan for Predicting Delta Evolution," WES *Technical Report HL-82-15* (Vicksburg: WES, 1982); and Flora C. Wang and William H. McAnally, "Mississippi River Meandering and Atchafalaya Delta Building," in *River Meandering. Proceedings of the Conference Rivers '83 Sponsored by the Waterway, Port, Coastal and Ocean Division of the American Society of Civil Engineers, October 24-26, 1983* (New York: American Society of Civil Engineers, 1984), 920-30.

6. McAnally, Heltzel, and Donnell, "Atchafalaya River Delta. Report 1."

7. William H. McAnally interview. For bay conditions, see Allen M. Teeter, "Investigations on Atchafalaya Bay Sediments," in *Proceedings of the Conference on Frontiers in Hydraulic Engineering Sponsored by the Hydraulics Division of the American Society of Civil Engineers, August 9-12, 1983* (New York: American Society of Civil Engineers, 1984), 85-90.

8. The Atchafalaya River Delta project led to the publication of 13 WES *Technical Reports*. An overview and summary is included in Barbara Park Donnell and Joseph V. Letter, Jr., "The Atchafalaya River Delta. Report 13: Summary Report of Delta Growth Predictions," WES *Technical Report HL-82-15* (Vicksburg: WES, 1992).

9. *HEC-6, Scour and Deposition in Rivers and Reservoirs. Generalized Computer Program, User's Manual* (U.S. Army Corps of Engineers Hydrologic Engineering Center, 1993).

10. Donnell and Letter, "Atchafalaya River Delta. Report 13."

11. McAnally interview.

12. Donnell and Letter, "Atchafalaya River Delta. Report 13."

13. For a general summary see Rita Robison, "Taming the Red River," *Civil Engineering* 65 (1995) 6: 64-66. More detail is provided in C. Fred Pinkard, Jr., "Red River Waterway Project: General Design," in William H. Espey, Jr., and Phil G. Combs, eds., *Water Resources Engineering: Proceedings of the First International Conference Sponsored by the Water Resources Engineering Division of the American Society of Civil Engineers, Aug. 14-18, 1995* (New York: American Society of Civil Engineers, 1996), 26-30.

14. James E. Foster, Charles R. O'Dell, and John J. Franco, "Development and Maintenance of Typical Navigation Channel, Red River, Hydraulic Model Investigation," WES *Technical Report HL-82-6* (Vicksburg: WES, 1982).

15. J.E. Foster, C.R. O'Dell, and J.E. Glover, "Channel Development in the Lower Reach of the Red River, Hydraulic Model Investigation," WES *Technical Report HL-87-9* (Vicksburg: WES, 1987).

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29. Ibid. Also Kuo-Chuin Wong, "The Response of the Delaware Estuary to the Combined Forcing from Chesapeake Bay and the Ocean," *Journal of Geophysical Research*, 96 (1991) C5: 8797-809.

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32. Keu W. Kim and Billy H. Johnson, "Assessment of Channel Deepening in the Delaware River and Bay: A Three-Dimensional Numerical Model Study," WES *Technical Report CHL-98-29* (Vicksburg: WES, 1998).

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35. Cost projections for COARF are included in *Deep Draft Navigation Design Course, 11-14 August 1980. Course Notes and References*, presentation by Roger Cook and enclosures 11 and 12 (Vicksburg: WES, 1980).

36. Carl J. Huval and Marden B. Boyd interviews.

37. An excellent overview is provided in Dennis W. Webb, "Navigation Channel Design Using Real-time Marine Simulator," in *Dredging '94: Proceedings of the Second International Conference on Dredging and Dredged Material Placement, Volume 2* (New York: American Society of Civil Engineers, 1994), 1081-91.

38. "Ship Simulation Saves $4 Million on Brownsville Channel," *TR News* 117 (1995) March-April, 30-1. Hewlett," Ship Navigation Simulation Study, Miami Harbor Navigation Improvement Project, Miami, Florida," WES *Technical Report HL-91-6* (1991); D.W. Webb and L.L. Daggett, "Use of Portable Simulator in Designing Channel Improvements for Port of Brownsville, Texas," *Proceedings of the ASCE Conference, Coastal Engineering Practice, '92, Long Beach, California* (New York: American Society of Civil Engineers, 1993); J.C. Hewlett, "Ship Navigation Simulation Study, Houston-Galveston Navigation Channel, Texas, Report 1, Houston Ship Channel, Bay Segment," WES Technical Report HL-94-3 (1994); and D.W. Webb,"Ship Navigation Simulation Study, San Juan Harbor, San Juan, Puerto Rico," WES *Technical Report HL-93-17* (1993).

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40. Ibid., 282. Also see Webb, "Ship Navigation Simulation Study, San Juan Harbor," WES *Technical Report HL-93-17*.

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69. "Columbia River Fish Mitigation: Endangered Species Act Listings," U.S. Army Corps of Engineers, Northwestern Division, Pacific Salmon Coordination Office, http://www.nwd.usace.army.mil/ps/species.htm.

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92. R. Charlie Berger, interview by author, Vicksburg, 26 July 1999.

93. Martin interview; Jourdan interview.

94. Ibid.; also McAnally, written comments to author.

95. "Labs support Bosnia peacekeepers," *Engineer Update*, March 1996; Major David Treleaven, "The Sava River Saga," *Florida Engineering Society Journal*, March 1996; "Americans in Bosnia: Building a bridge to peace," Clarion-Ledger (Jackson, Mississippi), 30 December 1995; Martin interview.

96. Ibid.; also Jourdan interview.

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98. Martin interview.

99. James R. Houston interview.

100. Ibid.

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102. Ibid. Unlike Whalin, who as WES Director pushed heavily for hiring Ph.D.s, Houston has preferred to hire engineers at the bachelors or masters level, then encourage further study.

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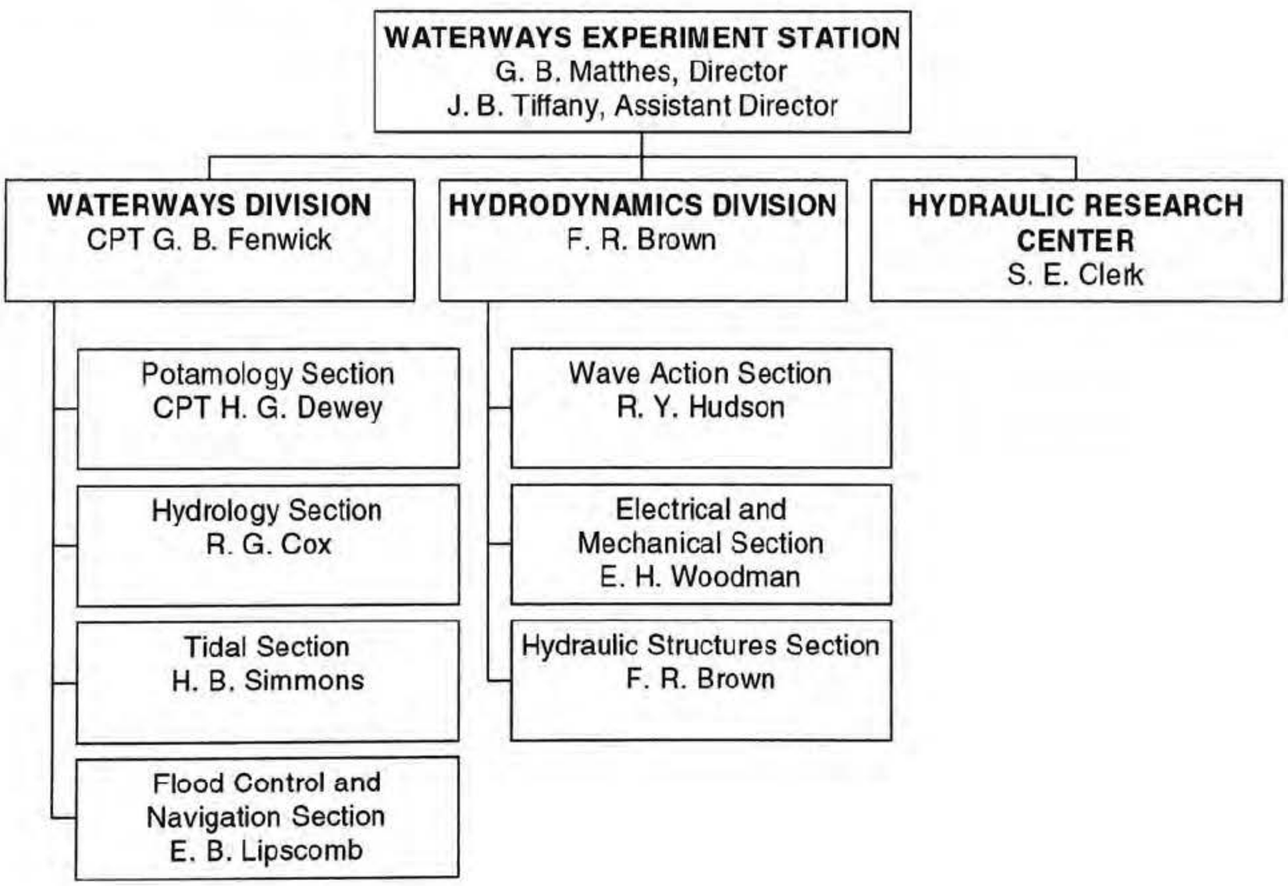
Appendix A
Organization Charts

Waterways Division, Hydrodynamics Division, and Hydraulic Research Center, 1943

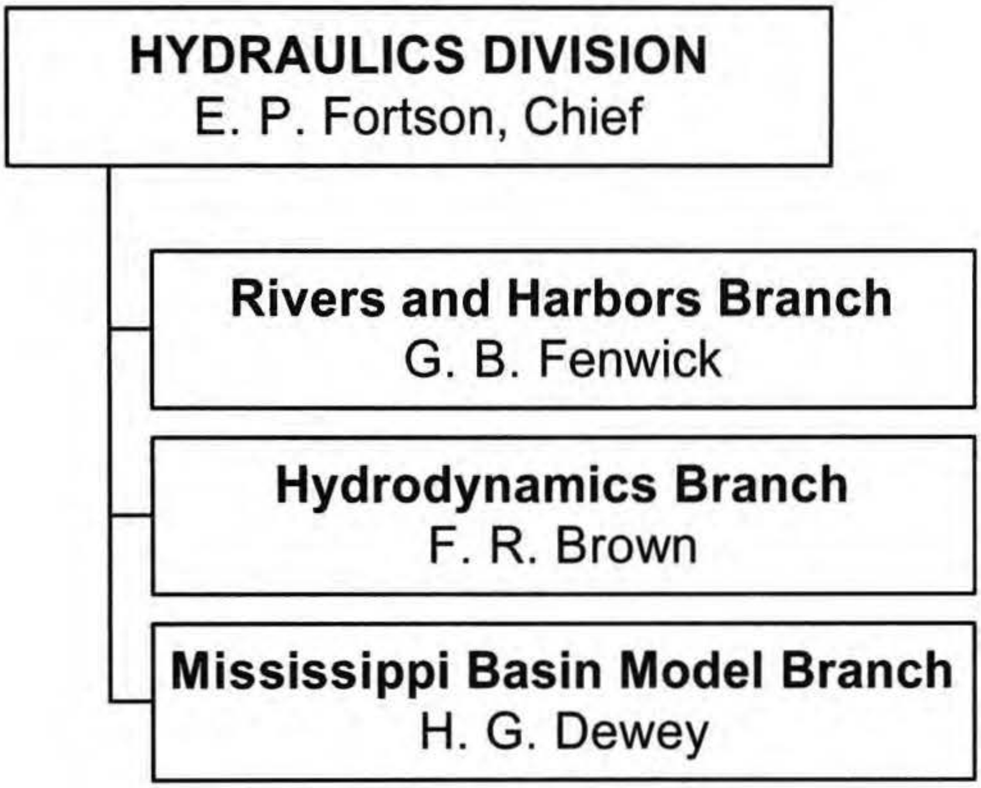


Hydraulics Division, 1945

HYDRAULICS DIVISION
G. B. Fenwick, Chief
F. R. Brown, Assistant Chief

- **Hydrodynamics Branch**
  R. Y. Hudson
- **Waterways Branch**
  E. B. Lipscomb
- **Instrumentation Branch**
  E. H. Woodman
- **Tidal and Salinity Branch**
  H. B. Simmons
- **Hydraulics Research Center**

Hydraulics Division, 1950



Note appearance of Mississippi Basin Model Branch.
Instrumentation Branch moved to Technical Service Division.

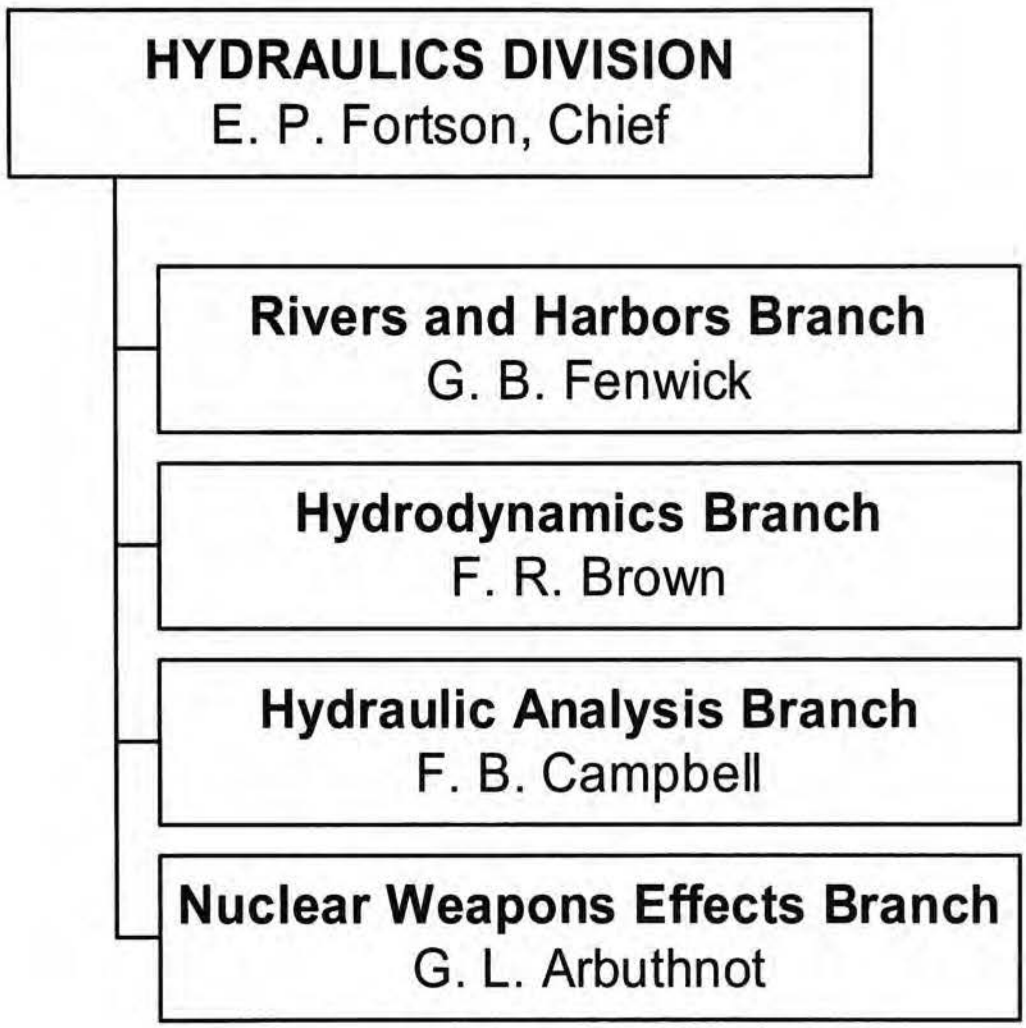
Hydraulics Division, 1955

HYDRAULICS DIVISION
E. P. Fortson, Chief

- **Rivers and Harbors Branch**
  G. B. Fenwick
- **Hydrodynamics Branch**
  F. R. Brown
- **Hydraulic Analysis Branch**
  F. B. Campbell

Note disappearance of Mississippi Basin Model Branch and appearance of Hydraulic Analysis Branch.

Hydraulics Division, 1962



Note appearance of Nuclear Weapons Effects Branch.

Hydraulics Division, 1963

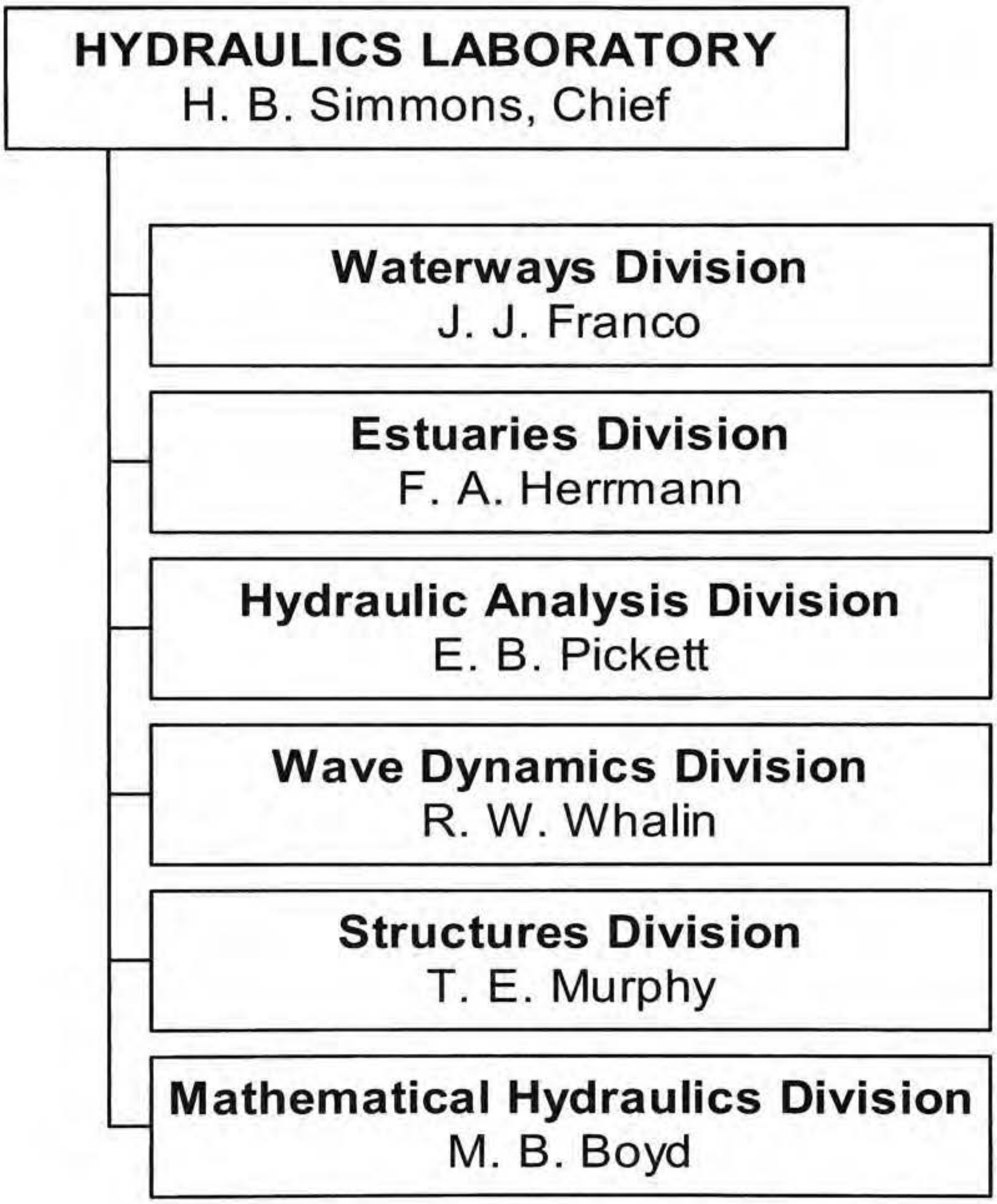
HYDRAULICS DIVISION
E. P. Fortson, Chief
G. B. Fenwick, Assistant Chief

- **Waterways Branch**
  J. J. Franco
- **Estuaries Branch**
  H. B. Simmons
- **Hydraulic Analysis Branch**
  F. B. Campbell
- **Water Waves Branch**
  R. Y. Hudson
- **Structures Branch**
  T. E. Murphy

Note disappearance of Rivers and Harbors Branch, Hydrodynamics Branch, and Nuclear Weapons Effects Branch.
Note appearance of Waterways Branch, Estuaries Branch, Water Waves Branch, and Structures Branch.

Fortson served temporarily in a dual assignment as chief, Hydraulics Division, and Acting Chief, Nuclear Weapons Effects Division. F. R. Brown became Chief, Nuclear Weapons Effects division.

Hydraulics Laboratory, 1973



Note change of title from Hydraulics Division to Hydraulics Laboratory.
Note appearance of Mathematical Hydraulics Division.

Hydraulics Laboratory, 1978

HYDRAULICS LABORATORY
H. B. Simmons, Chief
F. A. Herrmann, Assistant Chief

- **Waterways Division**
  J. E. Glover
- **Estuaries Division**
  R. A. Sager
- **Hydraulic Analysis Division**
  M. B. Boyd
- **Wave Dynamics Division**
  R. W. Whalin
- **Hydraulic Structures Division**
  J. L. Grace

Wave Dynamics Division moved from Hydraulics Laboratory to Coastal Engineering Research Center in 1983.

Hydraulics Laboratory, 1984

HYDRAULICS LABORATORY
F. A. Herrmann, Chief
R. A. Sager, Assistant Chief

- **Waterways Division**
  J. E. Glover
- **Estuaries Division**
  W. H. McAnally
- **Hydraulic Analysis Division**
  M. B. Boyd
- **Hydraulic Structures Division**
  J. L. Grace

Herrmann succeeded Simmons as Laboratory Chief in 1984.

Hydraulics Laboratory, 1988

HYDRAULICS LABORATORY
F. A. Herrmann, Chief
R. A. Sager, Assistant Chief

- **Waterways Division**
  M. B. Boyd
- **Estuaries Division**
  W. H. McAnally
- **Hydraulic Structures Division**
  G. A. Pickering

Note disappearance of Hydraulic Analysis Division.

Hydraulics Laboratory, 1996

HYDRAULICS LABORATORY
R. A. Sager, Acting Director
R. F. Athow, Acting Assistant Director

Waterways and Estuaries Division
W. H. McAnally

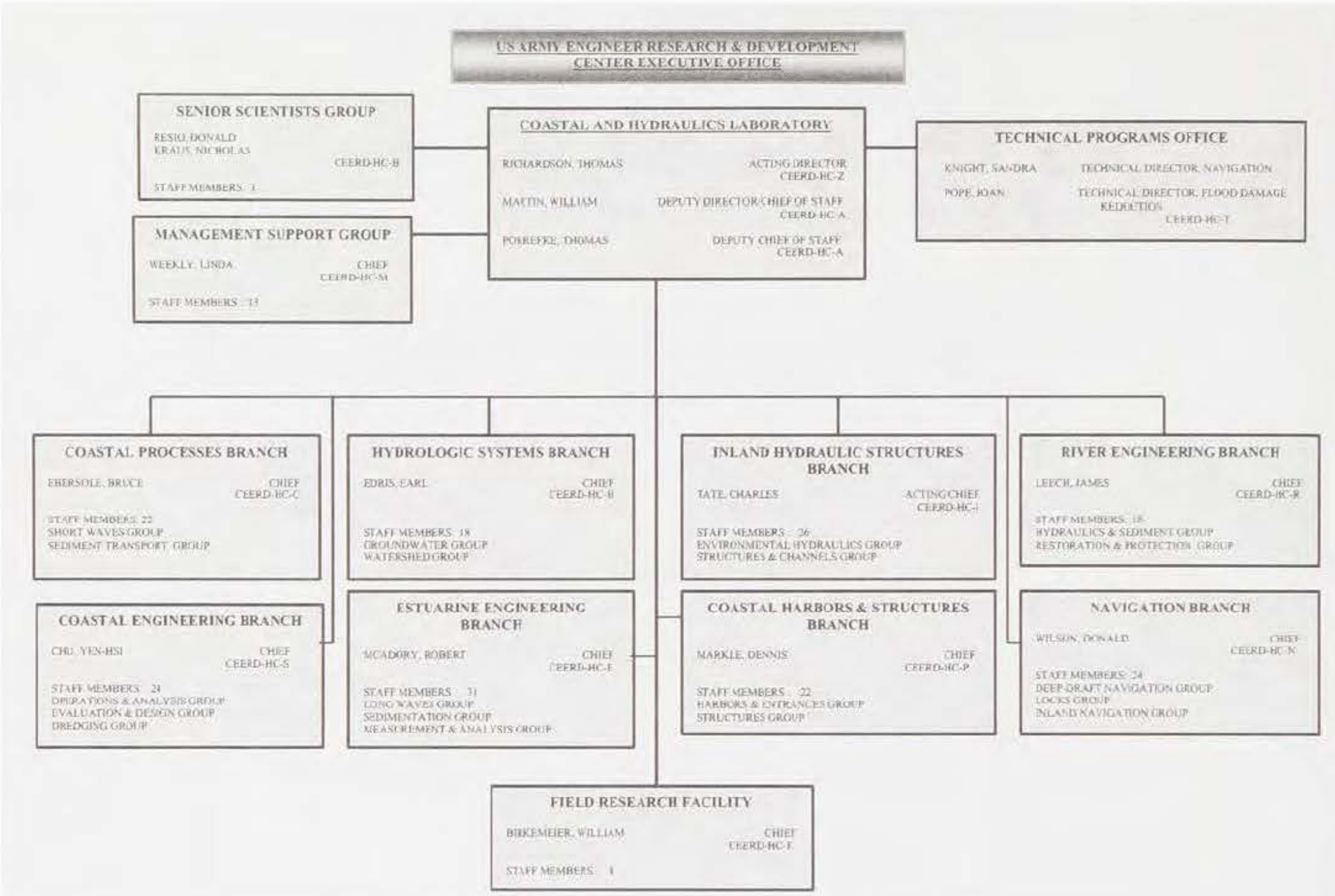
Navigation Division
L. L. Daggett

Hydraulic Structures Division
P. G. Combs

Hydro-Sciences Division
W. D. Martin

Herrmann retired in 1994.
Note merger of Estuaries and Waterways Divisions.
Note appearance of Navigation Division.
Note appearance of Hydro-Sciences Division.

Coastal and Hydraulics Laboratory, 2003



Appendix B
Projects in Progress – 1940, 1950, 1960, 1970

A list of WES projects in progress at ten year intervals provides an overview of the number, types, and sponsors of the Station's investigations in addition to illustrating the evolution of the WES engineering mission. The vast geographical extent of WES projects is especially impressive. There are no comprehensive lists of projects in progress in 1980 or 1990.

WES Hydraulics Division Investigations in Progress, December 1940

Flood-Control Dams (Spillways, Stilling Basins, and Conduits)

Project Title	*Sponsor*
Spillway and Stilling Basin Investigation, Arkabutla Dam, Coldwater River, Mississippi	Vicksburg District
Outlet Works Investigation, Arkabutla Dam, Coldwater River, Mississippi	Vicksburg District
Investigation of Intake for Outlet Structures, Bayou Bodcau Dam, Louisiana	Vicksburg District
Investigation of Spillway and Integral Sluices, Canton Dam, North Canadian River, Oklahoma	Tulsa District
Spillway Investigation, Denison Dam, Red River	Denison District
Spillway and Exit Channel Investigation, Experiment Station Dam, Durden Creek, Mississippi	Mississippi River Commission
Study of Structures for Future Power Development, Franklin Falls Dam, New Hampshire	Boston District
Spillway and Stilling Basin Investigation, John Martin Dam, Arkansas River	Caddoa District

Navigation Dams (Spillways and Stilling Basins)

Project Title	*Sponsor*
Fort Peck Dam, Tunnel No.1 Investigation	Missouri River Division

River Flood-Control Studies (Storage, Cutoffs, Confinements)

Project Title	*Sponsor*
Channel Improvement, Flood-Control Project, Johnstown, Pennsylvania	Pittsburgh District
Mill Creek Flood-Control Project, Cincinnati, Ohio	Cincinnati District
Mississippi River Flood-Control Model, Helena, Arkansas, to Donaldsonville, Louisiana	Mississippi River Commission

River Navigation Studies (Contractions, Realignments, Shoaling)

Project Title	*Sponsor*
Study of Plans for Elimination of Shoaling, Vicinity of Head of Passes, Mississippi River	New Orleans District

Tide and Wave Studies (Littoral Currents, Shoaling)

Project Title	*Sponsor*
Absecon Inlet, Improvement of Navigable Channel, Atlantic City, New Jersey	Philadelphia District
Study of Plans for Elimination of Shoaling in Richmond Harbor, James River, Virginia	Norfolk District
Study of Wave Action in Grand Marais Harbor, Minnesota	Duluth District
Model Study of Breakwater Locations in San Juan Harbor, Puerto Rico	U.S. Navy
Improvement and Maintenance of Navigation Channel, Savannah Harbor, Georgia	Savannah District
Study of Plans for Elimination of Shoaling in Deepwater Point, New Castle, and Finns Point Ranges, Delaware River	Philadelphia District
Study of Plans for Elimination of Shoaling in Wilmington Harbor, Christina River, Delaware	Philadelphia District
Wave Force Against Breakwaters	Great Lakes Division

Hydrological Studies

Project Title	*Sponsor*
Hydrological Research Project	Office, Chief of Engineers

Miscellaneous

Project Title	*Sponsor*
Study of Meandering of Model Streams	Mississippi River Commission
Study of Pump Suction Chamber, Drydock No. 4, Puget Sound Navy Yard	Bureau of Yards and Docks

WES Hydraulics Division Investigations in Progress, December 1950

Dams and Appurtenant Structures

Project Title	*Sponsor*
Belton Dam, Leon River, Texas, Comprehensive Model Study	Fort Worth District
Cheatham Dam, Cumberland River, Model Tests of Upstream Emergency Dam and Spillway	Nashville District
Model Studies of Folsom Dam, American River, California	Sacramento District
Model Studies of Fort Randall Dam	Omaha District
Garrison Dam and Reservoir, Missouri River, North Dakota, Model Studies of Outlet Works	Garrison District
Garrison Dam and Reservoir, Missouri River, North Dakota, Model Study of Spillway	Garrison District
Genegantslet Reservoir, New York, Model Study of Spillway	Baltimore District
Oahe Reservoir, Missouri River, South Dakota, Model Study of Outlet Works	Omaha District
Philpott Dam, Smith River, Virginia, Model Study of Spillway, Stilling Basin, and Conduits	Norfolk District
General Spillway Model Tests (No. CW 801)	Office, Chief of Engineers
Conduit Intake Model Tests (No. CW 802)	Office, Chief of Engineers
Cavitation Research (No. CW 806)	Office, Chief of Engineers
Sluice Outlet Model Tests (No. CW 812)	Office, Chief of Engineers
Model Study of Sluice Coaster Gate (No. CW 836)	Office, Chief of Engineers
Slide Gate Model Tests (No. CW 803)	Office, Chief of Engineers
Use of Air Instead of Water in Model Testing (No. CW 811)	Office, Chief of Engineers
Scale Effects on Spillway Discharge Coefficients (No. CW 819)	Office, Chief of Engineers

River Flood Control Studies

Project Title	*Sponsor*
Model Study of Flood-Control Project, Hoosic River, Adams, Massachusetts	New York District
Model Study of Flood-Control Project, Hoosic River, North Adams, Massachusetts	New York District
Mississippi Basin Model	Office, Chief of Engineers
Model Study of Memphis Harbor, Mississippi River	Memphis District
Hydraulic Capacity of Meandering Channels in Straight Floodways (No. CW 807)	Office, Chief of Engineers

River Navigation Studies

Project Title	*Sponsor*
Model Study of Mississippi River, Vicinity of Greenville Bridge	Vicksburg District

Tidal Area Studies

Project Title	*Sponsor*
Charleston Harbor, South Carolina, Model Study	Charleston District
Delaware River Model Study	Philadelphia District
Grays Harbor, Washington, Model Study	Seattle District
Raritan River, New Jersey, Model Study	New York District
Investigation and Model Study, Savannah Harbor, Georgia	Savannah District

Waves and Wave Action Studies

Project Title	*Sponsor*
Port Washington Harbor Model Study	Milwaukee District
Study of Wave Force on Breakwaters (No. CW 813)	Office, Chief of Engineers
Stability of Rubble-Mound Breakwaters (No. CW 815)	Office, Chief of Engineers

Study of Harbor Design (No. CW 822)	Office, Chief of Engineers
Scale Effects in Harbor Models (No. CW 833)	Office, Chief of Engineers

Miscellaneous

Project Title	*Sponsor*
Model Study of Niagara River	Buffalo District
Potamology Investigations	Mississippi River Commission
Analysis of Hydraulic Experimental Data (Model and Prototype) and Development of Design Criteria (No. CW 804)	Office, Chief of Engineers
Effects of Model Distortion on Hydraulic Elements (No. CW 809)	Office, Chief of Engineers
Simulation of Air Entrainment in Models Involving High Velocity Flow (No. CW 810)	Office, Chief of Engineers
Hydraulic Instrumentation (No. CW 827)	Office, Chief of Engineers
Development of Turbulence Meter (No. CW 837)	Office, Chief of Engineers
Prototype Analysis (No. CW 903-A)	Office, Chief of Engineers
Roughness Standards for Hydraulic Models (No. CW 818)	Office, Chief of Engineers

WES Hydraulics Division Investigations in Progress, December 1960

Dams and Appurtenant Structures

Project Title	*Sponsor*
Allegheny Dam, Allegheny River, Pennsylvania, Model Study of Spillway and Stilling Basin	Pittsburgh District
Big Bend Reservoir, Missouri River, South Dakota, Model Study of Spillway and Stilling Basin	Omaha District
Black Butte Dam, Stony Creek, California, Model Study of Outlet Works	Sacramento District
Carlyle Dam, Kaskaskia River, Illinois, Model Studies of Spillway and Stilling Basin	St. Louis District
Eufaula Dam, Canadian River, Oklahoma, Model Study of Spillway	Tulsa District
Everett Dam, Piscataquog, New Hampshire, Model Study of Spillway	New England Division
Gering Valley Project, Gering Valley, Nebraska, Model Study of Drop Structure	Omaha District
Greenup Dam, Ohio River, Model Study of Spillway Bulkheads	Ohio River Division
Jackson Dam, Tombigbee River, Alabama, Section Model Studies of Spillway	Mobile District
John Redmond Dam and Reservoir, Grand (Neosho) River, Kansas, Model Studies of Spillway and Stilling Basin	Tulsa District
Keystone Dam, Arkansas River, Oklahoma, General and Spillway Model Studies	Tulsa District
Markland Dam, Ohio River, Model Studies of Spillway Gate and Stilling Basin	Louisville District
Maxwell Dam, Monongahela River, Pennsylvania, Model Study of Spillway and Stilling Basin	Pittsburgh District
New Cumberland Dam, Ohio River, Model Study of Spillway Crest Gate, Stilling Basin, and Bulkhead	Pittsburgh District

Oahe Dam, Missouri River, South Dakota, Model Study of Spillway	Omaha District
Oahe Reservoir, Missouri River, South Dakota, Model Studies of Tunnels and Outlet Works	Omaha District
Pike Island Dam, Ohio River, West Virginia-Ohio, Model Study of Spillway and Stilling Basin	Pittsburgh District
Proctor Reservoir, Leon River, Texas, Model Study of Spillway	Fort Worth District
Red Rock Dam, Des Moines River, Iowa, Model Study of Stilling Basin and Conduit Outlet Portal	Rock Island District
Typical Flood- and Water- Control Structure Model Study, Central and Southern Florida Project (formerly "Typical Gated Spillway Structure Model Tests")	Jacksonville District
General Spillway Model Tests (CW No. 801)	Office, Chief of Engineers
Cavitation Research (CW No. 806)	Office, Chief of Engineers
Intake Emergency Gates (CW No. 836)	Office, Chief of Engineers
Riprap Protection at Hydraulic Structures (CW No. 840)	Office, Chief of Engineers

Harbors And Tidal Estuaries

Project Title	***Sponsor***
Delaware River Model Study	Philadelphia District
Galveston Bay, Texas, Model Study	Galveston District
Galveston Bay, Texas, Radioactive Tracer Tests of Sediment	Galveston District
Gulf Outlet Channel, Louisiana, Model Study	New Orleans District
Hudson River, New York, Model Study of Shoaling	New York District
Lake Pontchartrain, Louisiana, Model Study of Proposed Hurricane Structures	New Orleans District
Matagordo Ship Canal, Texas, Model Study	Galveston District

Narragansett Bay, Rhode Island, Model Study of Hurricane Tides	New England Division
Savannah Harbor, Georgia, Field Investigation and Model Study	Savannah District
Southwest Pass, Mississippi River, Model Study	New Orleans District
Investigation of Salinity Intrusion and Related Phenomena (CW No. 843)	Office, Chief of Engineers
Tides and Currents in Tidal Waterways (CW No. 845)	Office, Chief of Engineers
Mathematics of Flow in Tidal Inlets (CW No. 855)	Office, Chief of Engineers
Shoaling Processes (CW No. 856)	Office, Chief of Engineers
Arkansas River, Model Study of Typical Navigation Dam	Little Rock District
Barkley Lock and Dam, Cumberland River, Tennessee, Model Studies of Lock and Dam	Nashville District
Columbia Lock and Dam, Chattahoochee River, Alabama, General Model Studies	Mobile District
Dardanelle Lock and Dam, Arkansas River, Arkansas, Model Studies of Spillway, Lock, and Powerhouse Locations; Spillway Crest and Stilling Basin; and Lock Culverts and Intakes	Little Rock District
Greenup Locks and Dam, Ohio River, Model Study of Spillway and Stilling Basin	Huntington District
Jackson Lock and Dam, Tombigbee River, Alabama, Model Study of Navigation Conditions	Mobile District
Lock No. 19, Mississippi River, Keokuk, Iowa, Model Tests for Culvert Tainter Valves for New Lock	Rock Island District
Locks and Dam No. 4, Monongahela River Model Study of Navigation Conditions	Pittsburgh District
Maxwell Locks and Dam, Monongahela River, Model Study of Navigation Conditions	Pittsburgh District
McAlpine Locks and Dam (Locks and Dam No. 41), Ohio River, Model Study of Navigation Conditions	Louisville District
McAlpine Locks, Ohio River, Model Study for Modernization of Existing Lock	Louisville District

New Poe Lock, St. Marys River, Michigan, Model Study of Filling and Emptying System	Buffalo District
New Richmond Locks and Dam, Ohio River, General Model Study	Huntington District
Old River Lock, Louisiana, Model Study of Filling and Emptying System	Mississippi River Commission
Opossum Creek Locks and Dam, Ohio River, General Model Study	Pittsburgh District
Pike Island Locks and Dam, Ohio River, Model Study of Navigation Conditions	Pittsburgh District
Sacramento Barge Canal Lock, Sacramento River, California, Model Study of Filling and Emptying Characteristics	Sacramento District

River Flood Control

Project Title	*Sponsor*
Hoosic River, North Adams, Massachusetts, Model Study of Flood-Control Project	New York District
Lower Atchafalaya River Basin, Louisiana, Model Study	New Orleans District
Mississippi Basin Model	Office, Chief of Engineers
Turtle Creek Channel Improvement Model Study	Pittsburgh District

River Navigation

Project Title	*Sponsor*
Arkansas River Channel Model	Little Rock District
Arkansas River Navigation Model	Vicksburg District
Cornwall Island and Barnhart Island-Lake St. Francis Reaches, St. Lawrence River, Model Studies	Buffalo District
Buffalo Harbor, Lake Erie, Model Study of Approach Channel	Buffalo District
Conneaut Harbor, Ohio, Model Study of Wave Action	Buffalo District

Project Title	Sponsor
Duluth-Superior Harbor, Lake Superior, Model Study of Seiche Action	St. Paul District
Duluth-Superior Harbor, Superior Entry, Lake Superior, Model Study of Wave Action	St. Paul District
East Passage, Narragansett Bay, Rhode Island, Model Study of Wave Action	New England Division
Ice Harbor Dam and John Day Dam Projects, Washington and Oregon, Model Study of Riprap Requirements for Railroad Relocation Fills	Walla Walla District
Morro Bay, California, Design of Rubble-Mound Breakwater	Los Angeles District
Nawiliwili Harbor, Kauai, Hawaii, Model Study of Stability of Rubble-Mound Breakwater	Honolulu District
Stability of Rubble-Mound Breakwaters (CW No. 815)	Office, Chief of Engineers
Effects of Scale and Operating Techniques on Harbor Wave Action and Breakwater Models (CW No. 833)	Office, Chief of Engineers

Miscellaneous

Project Title	*Sponsor*
Garrison and Oahe Dams, Missouri River, South Dakota, Power Plant Transients Tests	Omaha District
Niagara Falls, New York, Model Study of Remedial Works	Buffalo District
Development of Hydraulic Design Criteria (CW No. 804) (formerly "Model and Prototype Analysis and Prototype Test Program")	Office, Chief of Engineers
Hydraulic Prototype Tests (CW No. 805)	Office, Chief of Engineers
Effects of Model Distortion on Hydraulic Elements (CW No. 809)	Office, Chief of Engineers
Siphon Action at Pumping Gates (CW No. 817)	Office, Chief of Engineers
Instrumentation (CW No. 827)	Office, Chief of Engineers
Water Temperature Effects on Bed Forms and Roughness (CW No. 841)	Office, Chief of Engineers

Ultrasonic Flow Measurement (CW No. 851)	Office, Chief of Engineers

Hydrology

Project Title	*Sponsor*
Development of Hydrologic Equipment (CW No. 173)	Office, Chief of Engineers

Electrical and Mechanical

Project Title	*Sponsor*
Operating Forces of Miter-Type Lock Gates (CW No. 300)	Office, Chief of Engineers

WES Hydraulics Laboratory Investigations in Progress, December 1970

Hydraulic Engineering and Design: Dams and Appurtenant Structures

Project Title	*Sponsor*
Alum Creek Dam, Alum Creek, Ohio, Model Study of Spillway	Huntington District
Arkansas River Dams, Model Study of Spillway Gates	Little Rock District
Barren River Dam, Barren River, Kentucky, Stilling Basin Pressure Tests	Louisville District
Branched Oak Dam, Nebraska, Model Study of Outlet Works	Omaha District
Cahokia Diversion Channel, Illinois, Model Study of Low Dam Replacement	St. Louis District
Clarence Cannon Dam, Salt River, Missouri, Model Study of Spillway	St. Louis District
Clinton and Fort Scott Outlet Works Model Studies, Wakarusa and Marmaton Rivers, Kansas	Kansas City District
Copan Dam, Little Caney River, Oklahoma, Model Study of Stilling Basin	Tulsa District
Drag Coefficients for Stilling Basin Baffles	Office, Chief of Engineers
Kaw Dam and Reservoir, Arkansas River, Oklahoma, Model Study of Spillway	Tulsa District
Meremac Park Reservoir, Meremac River, Missouri, Model Study of Outlet Works	St. Louis District
Nolin Dam, Nolin River, Kentucky, Prototype Tests, Gated Intake and Tunnel	Louisville District
Oakley Reservoir, Sangamon River, Illinois, Model Study of Spillway	Chicago District
Outlet Structure S-68 Model Study	Jacksonville District
Raystown Reservoir, Juniata River, Pennsylvania, Model Study of Gated Spillway	Baltimore District

Rowlesburg Dam, Cheat River, West Virginia, General Model Studies	Pittsburgh District
Salamonie Dam, Indiana, Prototype Flip Bucket Jet Trajectory Tests	Louisville District
Seabrook Outlet Structure Model Study	New Orleans District
Summersville Dam, Gauley River, West Virginia, Model Study	Huntington District
Summersville Lake, Gauley River, West Virginia, Prototype Valve Test	Huntington District
Tocks Island Dam, Delaware River, Pennsylvania, General Model Study	Philadelphia District
Trotters Shoals Dam and Reservoir, Savannah River, Georgia, Model Study of Spillway	Savannah District
West Point Dam, Chattahoochee River, Alabama-Georgia, Model Study of Diversion	Savannah District
General Spillway Model Tests (ES 801)	Office, Chief of Engineers
Cavitation Research (ES 806)	Office, Chief of Engineers
Riprap Protection at Hydraulic Structures (ES 840)	Office, Chief of Engineers
Stilling Basin Sidewall Pressure Fluctuations (ES 868)	Office, Chief of Engineers

Hydraulic Engineering and Design: Navigation Locks

Project Title	*Sponsor*
Bankhead Lock, Black Warrior River, Alabama, Model Study of Navigation Conditions and Development of Filling and Emptying System	Mobile District
Cannelton Locks and Dam, Indiana and Kentucky, Model Studies	Louisville District
Gallipolis Locks and Dam, Ohio River, Model Study of Navigation Conditions	Huntington District
Lock and Dam No. 8, Arkansas River, Model Study of Navigation Conditions	Little Rock District

Lock and Dam No. 13, Arkansas River, Model Study of Navigation Conditions	Little Rock District
Lock and Dam No. 14, Arkansas River, Model Study of Navigation Conditions	Little Rock District
Lock and Dam No. 17, Verdigris River, Oklahoma, Model Study of Navigation Conditions	Tulsa District
Locks and Dam No. 26, Mississippi River, Model Study	St. Louis District
Smithland Locks and Dam, Ohio River, General Model Study	Nashville District
Uniontown Lock and Dam, Ohio River, Model Study of Navigation Conditions	Louisville District
Lock Filling and Emptying Systems (ES 820)	Office, Chief of Engineers
Effect of Tow and Ship Size on Lockage Time (ES 872)	Office, Chief of Engineers

Hydraulic Engineering and Design: Channel Improvement for Flood Control or Navigation

Project Title	***Sponsor***
Arkansas, Verdigris, and Grand Rivers Confluence, Model Study	Tulsa District
Devil's Island Reach, Mississippi River, Model Study of Navigation Conditions	St. Louis District
Dike Design, Mississippi River	Memphis, Vicksburg, and New Orleans Districts
Investigation of Proposed Dike Systems, Mississippi River	Memphis, Vicksburg, and New Orleans Districts
Lake Erie-Lake Ontario Waterway Model Studies	Buffalo District
Little Rock Reach, Arkansas River, Model Study of Navigation Conditions	Little Rock District
Mississippi Basin Model	Office, Chief of Engineers
St. Louis Harbor, Mississippi River, Model Study of Navigation Conditions	St. Louis District
Shoaling at Harbor Entrances on the Mississippi River, Model Study	Memphis, Vicksburg, and New Orleans Districts

South Ellenville Flood Control Project, New York, Model Study	New York District
Van Buren Reach, Arkansas River, Model Study of Navigation Conditions	Little Rock District

Hydraulic Engineering and Design: Miscellaneous

Project Title	*Sponsor*
Chicago Sanitary and Ship Canal and Brandon Road Pool Surge Study	Chicago District
Energy Dissipators for Drainage Facilities	Office, Chief of Engineers
Erosion Control at Storm-Drain Outlets	Office, Chief of Engineers
Free Surface Vortex Research	Army Research Office
Mississippi River East Bank Barrier Levee Model Study	New Orleans District
Mound City Locks and Dam, System Analysis Considerations	Nashville District
St. Louis Harbor, Mississippi River, Missouri-Illinois, Prototype Wake Action Study	St. Louis District
Development of Hydraulic Design Criteria and Comprehensive Design Procedures (ES 804)	Office, Chief of Engineers
Hydraulic Prototype Tests (ES 805)	Office, Chief of Engineers
Effects of Model Distortion on Hydraulic Elements (ES 809)	Office, Chief of Engineers
Instrumentation, (ES 827)	Office, Chief of Engineers
Riprap Requirements in Channels	Office, Chief of Engineers
Resistance Coefficients for Channels Having Different Bed and Bank Roughness (ES 869)	Office, Chief of Engineers

Coastal Engineering: Harbors and Tidal Estuaries

Project Title	*Sponsor*
Barnegat Inlet, New Jersey, Model Study	Philadelphia District
Brunswick Harbor, Georgia, Model Study	Savannah District
Chesapeake and Delaware Canal Model Study	Philadelphia District
Chesapeake and Delaware Canal, Analytical Study of Salinity Intrusion	Philadelphia District
Chesapeake and Delaware Canal, Mathematical Modeling of Flow Conditions	Philadelphia District
Chesapeake Bay Model Study	Baltimore District
Columbia River Estuary, Entrance to Oak Point, Oregon and Washington, Model Study	Portland District
Comparison of Mathematical and Hydraulic Models for Harbor Oscillations	Coastal Engineering Research Center
Delaware River Model Study	Philadelphia District
Development of Mathematical Models for Estuaries	Coastal Engineering Research Center
Gastineau Channel, Alaska, Model Study	Alaska District
Grays Harbor, Washington, Model Study	Seattle District
Houston Ship Channel, Texas, Model Study	Galveston District
Jamaica Bay Hurricane Barrier Study, New York	New York District
James River 25-ft Channel Shoaling Studies	Norfolk District
Moriches Inlet, New York, Model Study	New York District
San Diego Bay, California, Model Study	Los Angeles District
Shrewsbury River, New Jersey, Model Study	New York District
Tillamook Bay, Oregon, Model Study	Portland District
Umpqua River Estuary, Oregon, Model Study	Portland District
Investigation of Salinity Intrusion and Related Phenomena (ES 843)	Office, Chief of Engineers

Tidal Currents in Tidal Waterways (ES 845)	Office, Chief of Engineers
Shoaling Processes (ES 856)	Office, Chief of Engineers
General Coastal Inlet Studies (ES 869)	Office, Chief of Engineers

Coastal Engineering: Shore Protection, Wave Action, and Beach Processes

Project Title	*Sponsor*
Chagrin River, Eastland, Ohio, Model Study of Wave Protection Structures	Buffalo District
Crescent City, California, Flume Tests for Tsunami Study	San Francisco District
Humboldt Bay, California, Model Study of Designs for Jetty Repairs	San Francisco District
Limiting Values of Wave Refraction Coefficients	Office, Chief of Engineers
Texas Coast Hurricane Surge Model Studies	Galveston District
Criteria for the Design of Small-Boat Harbors (ES 863)	Office, Chief of Engineers

Coastal Engineering: Breakwater Design and Performance

Project Title	*Sponsor*
Oak Harbor, Washington, Model Study of Floating Breakwater	Seattle District
Vermillion Harbor, Ohio, Model Study	Buffalo District
Wave Force on Breakwaters (ES 813)	Office, Chief of Engineers
Stability of Rubble-Mound Breakwaters (ES 815)	Office, Chief of Engineers
Investigation of Wave Reflecting and Transmitting Characteristics of Rubble-Mound Breakwaters, Rubble Wave Absorbers, Sand Beaches, Wave Traps, and Resonators (ES 853)	Office, Chief of Engineers

Hydrology and Water Quality

Project Title	*Sponsor*
Diffusion Tests in Estuary Models for Office of Saline Water	Department of the Interior
Dilution and Dispersion of Desalination Plant Effluent	Department of the Interior
PECo Thermal Studies, Delaware River Model	Philadelphia District
St. Clair River, Model Study of Submerged Sills	Detroit District
Development of Hydrologic Equipment (ES 173)	Office, Chief of Engineers
Water Temperature Effects on Bed Forms and Roughness (ES 841)	Office, Chief of Engineers
Mechanics of Flow in Stratified Reservoirs (ES 870)	Office, Chief of Engineers

Appendix C
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Interviews

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